Investigating the Characterisation of Temperatures Within New Zealand Buildings

A thesis presented in partial fulfilment
of the requirements for the degree of
Master of Science in Physics
at Massey University

Andrew Richard POLLARD
October 2001

"Science is facts; just as houses are made of stones, so is science made of facts; but a pile of stones is not a house and a collection of facts is not necessarily science."

– Henri Poincaré

ABSTRACT

The variations in indoor temperatures between New Zealand buildings can be due to differences in the behaviour of the occupants (for example how frequently the building is occupied) or due to physical differences between the buildings (such as differing insulation levels or degree of shading).

This thesis will look at some physical processes that give rise to temperature variations and will look to see how the overall variation in temperatures is affected by these physical properties.

One systematic physical process affecting the indoor temperature within a building occurs when the area being considered is small (such as the living room of a house) and the degree of heat flow into the room is reasonably large, the temperature within the room will then have a tendency to increase with height resulting in a vertical temperature gradient. Detailed vertical temperature distributions are examined for two houses.

Another source of variation is the differences in temperatures throughout a building. This examines the extent to which buildings are only partially heated. This has briefly been examined in this thesis by examining the contrasts between the temperature measurements throughout a set of nine houses.

Some sources of physical temperature variation within a building can be unpredictable. Localised temperature anomalies can be due to the presence of specific heat flows (frequently from household appliances). This thesis contains examples of these localised sources and provides guidance for placing temperature sensors to minimise localised effects.

ACKNOWLEDGEMENTS

I would like to thank my supervisors at Massey University, Bob O'Driscoll and Neil Pinder, for their encouragement, getting me to focus on the appropriate issues, discussions on report writing and other topical discussions. I am most grateful and have learnt much from them on research methods.

I would also like to thank a number of my colleagues (past and present) at the Building Research Association of New Zealand (BRANZ) who have helped me with my work on temperatures; Albrecht Stoecklein, Nigel Isaacs, Michael Camilleri, Roman Jaques, Lynda Amitrano, Jeremy Tries, Sarah Bishop and Susan Dickinson.

Thanks are also due to Michael Camilleri for helping me with programming in `S-PLUS` and for making available a number of data processing routines he has written.

The temperature logger used to monitor the temperatures in All Saints Church, Palmerston North, was a prototype BRANZ Microvolt Logger developed by Sean Flanagan and Ian Cox-Smith. I would like to thank both of them for their work with the loggers and their assistance with my use of them in All Saints Church.

I would also like to thank Norm Wood for his development of the BRANZ Temperature Logger (originally developed by Sean Flanagan and Ian Cox-Smith) and his helping me to understand this and other data loggers better.

Both understanding and undertaking calibrations formed a significant part of this project and Ian Cox-Smith, Roger Stanford and Daniel Jang require thanking particularly.

Thanks to Lloyd Love for his discussions on heating options for All Saints Church.

I also need to thank Bob O'Driscoll for holding the ladder still while I was installing the thermocouples into All Saints Church.

This research would not have been possible had it not been for Bob O'Driscoll, Roman Jaques and the Household Energy End-Use Project (HEEP) homeowners for kindly allowing the use of their houses for the installation of data logging equipment.

I am indebted to family, friends and colleagues for their unwavering support for me while I have been undertaking this work. Thanks.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

It is estimated that people in developed countries spend over 80% of their time inside buildings. It is important that conditions inside buildings be both healthy and comfortable and that providing such conditions is environmentally sustainable and affordable.

There is little current quantitative information on the indoor conditions in New Zealand buildings. Present information suggests that a number New Zealanders are living in poor housing, whose damp and cold indoor conditions are causing health problems (National Health Committee 1998). Cold indoor temperatures are more likely to occur during winter and an increase in the deaths in New Zealand over winter has been observed (Isaacs and Donn 1989). The health of New Zealanders will be improved by specific interventions to improve the heating, insulation and ventilation within houses that have poor indoor conditions (Bowers 1998).

How the present indoor conditions in New Zealand houses satisfy the comfort expectations of the occupants is also not well understood. Comfort is an important determinant for space heating in houses (Seligman, Darley and Becker 1978). The Household Energy End-use Project (HEEP) is currently measuring indoor temperatures and space heating in New Zealand houses and has found that almost 50% of households currently surveyed report that their heating system did not always achieve comfortable conditions as reported by the occupants at the time of surveying (Stoecklein 2001). By understanding the drivers of comfort and knowing how these are changing over time, a better prediction of the future space heating energy use and the resulting indoor temperatures will be possible.

The largest environmental impact in providing suitable indoor conditions in New Zealand houses is the energy used for space heating. It is environmentally responsible to minimise this energy usage. The amount of energy used for space heating can be minimised by reducing the amount of heating required to provide suitable conditions within the house (by making improvements to the building such as increasing the insulation level) or by using more efficient space heating systems (such as heat pumps which use two to three times less energy than an electric oil-column heater). Both improvements to the building and to the heating system used within it, usually involve a trade-off between set-up (purchase) costs and operational (energy) costs. For a particular energy conservation measure (such as the installation of ceiling insulation), lower operational costs (less space heating is required) usually come at the cost of the particular energy conservation measure (cost of the insulation). Options to minimise energy use may be complicated by the financial restraints of the occupants.

Low-income households spend a greater proportion of their income on energy usage than those households on higher incomes (Isaacs 1998) and may not have the disposable income available to implement energy conservation measures. Low-income households are also more likely to live in rented accommodation where the building owner has already decided many of the options. As the set-up costs falls upon the building owner and the operating costs fall upon the building occupant for many energy conservation options, it is not uncommon for rental properties to be poorly insulated or to have inefficient heating systems installed within them.

A good understanding of the indoor conditions will help to confirm whether the actions put in place to ensure healthy and comfortable houses are effective. The measurement of indoor conditions is an important part of developing this understanding.

Chapter 2

Indoor Conditions

This chapter begins with an examination of how the indoor conditions within a building are related to the building energy performance, occupant health and occupant comfort. Later in this chapter, the practicalities of characterising the indoor conditions in a collection of buildings are considered and finally this chapter concludes with a description of the experimental approach for this thesis.

2.1 Building Energy Performance

There are a number of potential fields throughout a building and its immediate environment. These include temperature, atmospheric pressure, and partial pressures of various volatile materials (including water). These spatially and temporally varying potential fields give rise to a dynamic relationship between the indoor conditions and the immediate external environment. The indoor conditions generally refer to the "conditioned space" inside of a building, i.e. the areas that are usually occupied and heated and cooled by people, excluding such areas as the roof space and subfloor space.

In examining a dynamic situation it is useful to consider the conservation laws and those variables that are conserved. The first law of thermodynamics can be applied to the building and the external environment and states

$$dU = dQ - dW \tag{2.1}$$

where dU is the change in the energy stored in the building, dQ is the heat flow into the building and dW is the work done by the space within the building on the surroundings. Each of these terms can be further broken down into a number of contributing terms. The size of these various energies will impact on the resulting indoor conditions (in particular, the temperature) within the building.

2.1.1 Energy Storage

The energy storage of the building, U, is determined by the thermal heat capacities of the indoor air, the building materials and the other items (furnishings) within the building. The building materials form a large part of the overall thermal capacity. The thermal capacity of the building materials is known as the thermal mass of the building. Increasing the thermal mass of a building has the effect of buffering the indoor temperatures from changes in the heat flowing into, or out of, the conditioned space. Buildings that have a high thermal mass are frequently constructed from materials that are quite dense such as concrete. A common way of increasing the thermal mass of a building is to increase the amount of dense material used within them. Thermal mass has been examined by Balcomb (1983) and its application to New Zealand conditions by Donn and Thomas (2001), Bellamy and MacKenzie (1999), Pollard and Stoecklein (1998) and Isaacs and Donn (1994). The accessibility of the thermal mass to the conditioned space inside a building structure is an important issue in the usability of the heat stored within the thermal mass.

2.1.2 Heat Conduction

While thermal mass buffers the indoor temperature, raising or lowering the mean temperature level requires adjustment to the heat flows into, or out of, the building. The heat loss through each element for a standard small uninsulated building and a typical insulated building are shown in Figure 2.1.

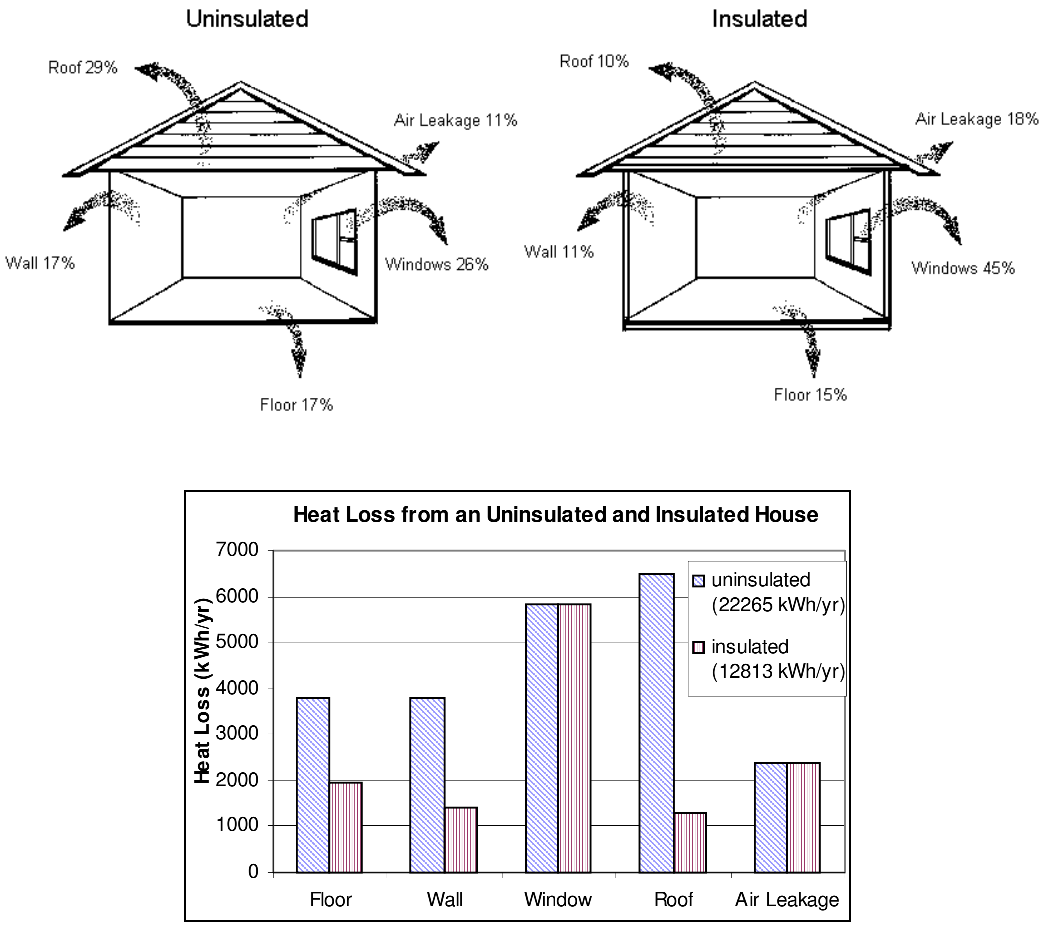


Figure 2.1 Approximate heat loss for a small building located in Christchurch

Fourier’s law of heat conduction states that heat will flow by from an area of higher temperature to an area of lower temperature. Generally over winter, conduction will occur from the air inside a building to the air outside. The rate of heat flow is dependent on the temperature difference and the thermal resistance of the material through which the heat is flowing. Insulation with a high thermal resistance (R-value) is used in buildings to limit the heat flow between the inside and the outside of a building. Care must be taken with the building design and placement of the insulation, if pathways of lower thermal resistance (‘thermal bridges’) are to be avoided (see chapter 39, ASHRAE 1995). The detailing at edges and corners and around windows is especially important (Cox-Smith 2001). An estimate of the total thermal resistance of an assembly of building materials and insulation needs to take into account the many heat flow paths available (Muncey 1982). Also the temperatures of both the inside and outside air can vary considerably so the conduction heat flow can be quite variable.

2.1.3 Solar Radiation

Solar radiation is a source of heat gain to buildings. Solar radiation incident on a building can be directly from the sun (direct normal solar radiation) or from scattering, reflection, or re-radiation (diffuse solar radiation) of solar radiation (Kimura 1977). While the radiation incident on the building exterior is required to diffuse through the building envelope before it can influence the inside of the building, the solar gains through windows are immediately available to heat the inside surfaces of the building and so readily affect the radiant temperature field (ISO 1985, McIntyre 1980) within in the building. While glass is transparent to the short wave radiation of direct normal solar radiation it is reasonably opaque to the long wave radiation emitted by the surfaces within the building.

Heat gains from solar energy are desirable in winter when the indoor temperatures generally need to be raised. However in summer conditions or in highly glazed commercial buildings, overheating can be a problem and it may be desirable to exclude solar radiation from entering the building. The number, size and placement of windows together with design features such as overhangs, eaves, sidefins and awnings are methods to control the solar gains of the building. The reflection, absorption and transmission properties of the glass also affect the degree to which solar radiation can influence the indoor conditions. Windows have a lower R-value than walls. The use of a large proportion of the wall area for windows results in increased heat loss by conduction. New Zealand has a tradition of using a high proportion of the wall area for windows. As was seen in Figure 2.1, the heat losses through windows become a large proportion of the total heat loss in well-insulated buildings and the use of advanced glazing and window systems becomes more important.

2.1.4 Ventilation

The air inside a building needs to be exchanged with fresh air to reduce the concentration of carbon dioxide (CO_2), moisture and other contaminants (WHO 2000, DOE 2000b). The fresh outside air generally has a lower enthalpy than the indoor air that it is replacing. Outside air naturally enters a building through cracks and gaps in the building envelope (infiltration) due to pressure differences between the inside air and the outside air (Chastain and Colliver 1989). For large commercial buildings, use is made of mechanical ventilation to ensure there is a regular exchange of indoor air with fresh air. Deliberate ventilation within detached housing more commonly occurs by opening windows. Extractor fans and range hoods may be used in areas such bathrooms or kitchens where containments such as moisture or odours occur.

2.1.5 Space Heating and Internal Gains

Heat is also created within a building. An obvious source of this heat is from space heating. Approximately 36% of New Zealand's residential energy consumption is used for space heating according to a 1995 estimate from the Energy Efficiency and Conservation Authority's (EECA) Energy End-Use Database (EECA 2000). Residential space cooling during summer does occur, but the energy used is very much less than that used for space heating. In large commercial buildings, both space heating and cooling are important. However the breakdown of energy use for commercial buildings varies depending on the functional use of the building (p60, Baird, Donn and Pool 1983).

Heaters have a range of energy efficiencies ranging from the low efficiencies (about 10%, see Todd 2001) of open fires, which lose a considerable proportion of their heat with the exhaust gases up the chimney, to the high efficiencies of heat pumps which generate two to three times the heat output as the energy input. A wider environmental impact report on heaters would include issues such as the greenhouse gas emissions of each heater and type of fuel used.

Heaters can affect both the air temperature and radiant temperature of the space in which they are operating. Heaters such as an oil column heater will more readily heat the air by conduction and convection than an electric bar radiant heater, which more rapidly increases the radiant temperature (the average temperature of surrounding surfaces) within the conditioned space.

Many other appliances in the house (ovens, hobs, irons, etc.) are sources of heat that is released into the building. Appliances can also release heat as a by-product of their main purpose (fridges, TV's, etc.). The heat gained from appliances not used for space heating is called equipment gain.

Heaters and appliances may also have other impacts on the humidity levels inside the building. As part of the combustion process, flueless gas heaters release large amounts of moisture as well as combustion products (CO_2 and CO) into the space in which they are operating. Additional ventilation is required to reduce the concentrations of these contaminates. Dehumidifiers are another example of an appliance that affects the humidity level in the house.

The occupants themselves also generate heat within a building (internal gains). The amount of heat generated is dependent on the number of occupants their activity level and degree of clothing.

2.1.6 Building Performance

Once a building has been designed and constructed, the manner of the response of the indoor conditions to changes in the environment (air temperatures, solar radiation) and/or operation of the building (amount of heating and cooling, level of occupancy) is determined. As the environmental factors are beyond the control of the occupants it is largely left to the occupant to adjust the indoor conditions with space heating (or space cooling). Appropriate design, however, can reduce the need for additional space heating to small amounts (Vale and Vale 2001).

With the large number of individual heat flow mechanisms involved for a building the use of computer programs to calculate the heat flows has become common. The website http://www.eren.doe.gov/buildings/tools_directory contains a number of links to computer models that vary in sophistication. A number of these programs have been used in New Zealand. For example, the revision of the thermal insulation standard for New Zealand houses (Standards New Zealand 1996), made use of the computer program SUNCODE (Wheeling and Palmiter 1985) to examine the impact of increased levels of insulation on the space heating energy requirements for new housing subject to idealised temperature requirements (Stoecklein 1995).

2.1.7 Occupant Variation

A large uncertainty in understanding the variation in space heating energy use in buildings is due to a lack of knowledge of what occupants want for the indoor conditions in buildings. When improvements such as increased levels of insulation are made to house, so that the existing indoor conditions can be obtained with less space heating, it is frequently observed that only a fraction of the reduction possible is taken up (see for example, Seligman, Darley and Becker 1978 or pp. 24-25, Bell, Lowe and Roberts 1996). It has been suggested that the additional space heating has been used to provide higher room temperatures or a longer time of heating than was achieved before the improvements were made. The reductions in predicted energy savings due to increased service (comfort) is termed ‘takeback’ or ‘clawback’ (Williamson 1997).

An important building science study was undertaken in the 1970s on a recently built planned housing development at Twin Rivers, New Jersey, USA (Socolow 1978). As part of this study, Seligman, Darley and Becker (1978) observed that the energy consumption of 28 identical townhouses varied by a factor of two between the highest consumer and the lowest consumer. From an attitudinal survey of these 28 houses, two factors (from a factor analysis) emerged as correlating well with the energy consumption of the house. The most important factor (having a coefficient of determination (R^2) of 0.30 with the energy consumption) summarised attitudes concerning comfort and health in the use of air conditioning. A second factor (with a R^2 of 0.25) was related to the level of effort required to conserve energy in order to obtain monetary savings.

In another part of this study, Sonderegger (1978) examined the variation of energy used for space heating between 205 similar units by examining monthly billing records between 1971 and 1974 (the natural gas consumption of the units was predominantly space heating). The statistically observable differences were: the number of bedrooms in the unit, whether the unit had double-glazing and whether the unit was an end unit or not. Using multiple regression, these three factors account for 54% of the total observed variation in energy use. Sonderegger was interested in examining the remaining 46% of the variation. In the 205 townhouses, 52 had a change of occupants (“movers”) between the winters of 1971/72 and 1973/74. The remaining 153 townhouses had no change of occupants (“stayers”). By carefully examining pairs of movers and stayers, Sonderegger was able to show that of the unexplained variation, 29% was due to persistent house-related quality issues (quality of construction, variation in raw materials) with the remaining variation attributed to occupant-related issues; 38% due to persistent (“lifestyle”) patterns (like thermal preference and the usage of drapes) and 33% due to non-persistent (“change”) patterns (such as children being born, changes in employment, changes to house, the purchase of additional appliances).

In summary, occupants are an important source of variation in the energy usage in buildings. Occupant related issues relate to both one-off events and general lifestyle patterns. An important aspect of lifestyle appears to be attitudes towards comfort and health. In the next two subsections, the relationship between health and comfort to indoor conditions will be further examined.

2.2 Health

Linkages between occupant health and indoor conditions are difficult to establish. Much of the work done has been observational, but unfortunately few measurements have been made of the indoor conditions encountered within residential buildings (Markus 1994). Damp and cold indoor conditions have been identified (National Health Committee 1998) as key properties of the indoor conditions that have a detrimental effect on the health of the occupants.

2.2.1 High Humidity

High humidity (damp) air is not harmful in itself. Upper tract respiratory illness has a greater association with low relative humidity levels of less than 40% (Mant and Gray 1986). Relative humidity levels greater than 70% however promote the growth of moulds, which can cause allergic (fungal) reaction or infection. Surface condensation also plays a role in mould growth. Surface condensation is created when highly humid air comes into contact with cold surfaces. Clause E3 of the New Zealand Building Code (NZBC) (see Isaacs, 1999) is concerned with reducing the likelihood of surface condensation by specifying minimum thermal resistance values (R-values) for building materials so that surface temperatures are less likely to be low enough to cause condensation problems.

Dust mites are an important environmental allergen in asthma (Raw and Hamilton 1995). Dust mite growth is favourable at high humidity levels. However it is important to consider the microclimate in which the dust mites inhabit as these conditions can differ markedly from the ambient room climate (Cunningham 1996).

2.2.2 Cold Temperatures

The humidity and temperature properties of a fixed volume of air are related. The properties of moist air (psychrometrics) are discussed in chapter 6 of the ASHRAE Fundamentals (ASHRAE 1997). When the temperature of the air is increased (with no additional moisture added) the relative humidity decreases and when the temperature of the air is decreased the relative humidity increases until the saturation point is reached.

Indoor conditions with high humidity (dampness) have been identified as a health concern due to the increased presence of fungi and allergens that have been connected to illness. Low temperatures appear to primarily have a physiological impact on health. When temperatures below 16°C are encountered it is believed that the risk of respiratory infection increases (Raw 1988). Below 12°C there is an increase in cardiovascular strain increasing the risk of heart attack or stroke. As the temperature decreases there is also a general increase in the risk of hypothermia and an increase in accidents due to reduced muscular control.

Coldness has been seen to be a health concern due to the increase in seasonal deaths during winter (seasonal mortality). In countries where the indoor temperature is colder, the seasonal mortality rate is generally higher (pp. 144, Boardman 1991). New Zealand's seasonal mortality (Isaacs and Donn 1989) is high in comparison to many countries, with lower rates being recorded in countries like Sweden and the USA which have a much more severe climate.

2.2.3 Indoor Temperatures in New Zealand

Measurements of indoor temperatures in New Zealand houses have been limited. In 1971-1972, as part of the 1971 Electricity Survey (Department of Statistics 1972), 1651 houses were randomly selected throughout the country to examine electricity usage. As part of this study, an examination of the effectiveness of insulation on energy usage and indoor temperatures was made. Of the 1651 sample houses, 223 had fully insulated ceilings. Attempts to match these fully insulated ceiling houses with similar houses (region, roof materials, wall materials, income of head-of-household and number of occupants) in the remaining non-fully insulated ceiling houses resulted in 100 houses able to be matched. A further 95 houses from the non-fully insulated ceiling houses were randomly selected for use as a control comparison sub-sample. Consequently temperature measurements were made in 195 houses (Department of Statistics, 1976). Two periods were considered, August-September, 1971 and February-March, 1972. The temperatures were recorded electrochemically – and give the mean temperature over the measured period. Sensors were placed in the kitchen, lounge, and the main bedroom for each of the sampled houses. The mean temperature for the complete sample for each period and each room is shown in Table 2.1. The random sub-sample shows the overall sample is not markedly different so the full sample will be taken as reasonably representative of New Zealand households.

Table 2.1 Temperatures in New Zealand houses in 1971-72

Location within House	**August – September 1971 Temperature (°C)**	**February – March 1972 Temperature (°C)**
Kitchen	16.3	20.6
Lounge	16.0	20.5
Main Bedroom	14.6	19.7

These mean temperatures are low compared with international studies (Widegren-Dafgård, 1984) however comparison with other countries is not straightforward due to differences in the experimental methods used. For example, in 1978, temperatures were measured in 1000 UK households (Hunt and Gidman 1982). While acknowledging the desirability of continuous measurement, this study was limited to spot measurements of the indoor conditions. About one quarter of the houses were measured in the morning, one quarter in the afternoon and the remaining half in the evening. The average temperatures found in this UK study were 16.7°C for the kitchen, 18.3°C for the living room and 15.2°C for the master bedroom. As the spot temperatures are likely to be higher than the mean temperatures, the results from the two studies cannot be directly compared but the similar results are apparent.

Care must also be taken as to where the temperatures are measured within the houses. Fuller and Minogue (1981) measured the indoor temperatures in 21 typical Irish houses. These measurements were made 150 mm from the ceiling within a number of rooms within each of the houses. In order to estimate the 'volumetric mean air temperature' corrections were made to the measured temperatures based on the type of heating system present.

In the UK from 1950 to 1980, mean indoor temperatures in living rooms have been increasing by about 1°C per decade while evening temperatures in living rooms appear to have reached a plateau (Shorrock and Henderson 1990). It is interesting to see if similar trends have occurred in New Zealand.

Between 1985 and 1987 Breuer (1988) measured the thermal performance of a number of houses throughout New Zealand. The occupants in 23 of these households recorded the daily minimum and daily maximum indoor temperatures measured in their living room. Breuer (1988) presents the monthly average of the daily mean temperatures for each house subject to the availability of data. Seventeen houses had measurements for August and September 1987 with an average temperature of 17.5°C. As this research focused on solar design and included a number of solar designed houses, the buildings cannot be regarded as representative of New Zealand houses and cannot be directly compared to the temperatures measured in 1971.

Other temperature measurements in New Zealand have been restricted in the number of houses measured at any one time (Stoecklein *et al.* 2000, Fitzgerald and Ryan 1996). However as programmes continue, the number of houses monitored will increase but comparison of temperatures from different years will require consideration of the severity of the weather each year (Pollard, Stoecklein and Bishop 1997).

The National Health Committee (1998) also notes that poor quality housing also has a detrimental impact on mental health. Whether people find the indoor conditions thermally comfortable would be one impact on mental well being. The next section examines thermal comfort in more detail.

2.3 Thermal Comfort

Thermal comfort is frequently defined as that condition of mind, which expresses satisfaction with the thermal environment. A number of personal, environmental and contributing factors influence the acceptability and satisfaction of the thermal environment (see for example, Innova 1997). These factors generally relate to the ability of the human body to maintain a normal constant core temperature and are further discussed below.

2.3.1 Personal Factors

Heat is created within the human body due to fundamental biological processes and muscular actions. The metabolic heat generated by a person will vary depending on the level of physical activity the person is currently engaged in. Metabolic rates are typically tabulated for a person as the energy produced per unit surface area of the body (An average man has a surface area of about 1.8 m^2). A unit called the met (1 met = $58.2\ W\cdot\ m^{-2}$) is frequently used. 1 met is the metabolic rate of a person seated at rest. For other metabolic rates see tabulated data such as that in the ASHRAE Fundamentals (page 8.6, ASHRAE 1997).

The other personal factor, in addition to the metabolic rate, is the level of insulation provided by the clothing the person is wearing. Again rather than direct measurements tabulated values for clothing ensembles and individual clothing items are common (page 8.8, ASHRAE 1997). A unit called the clo is used where 1 clo = $0.155\ m^2\cdot\ K\cdot\ W^{-1}$. A typical business suit has an insulation value of about 1 clo.

2.3.2 Environmental Factors

The heat loss from a person to the environment also depends upon the conductive, convective, evaporative and radiative properties of the environment. These properties are characterised by the air temperature, the air movement, the humidity of the air and the radiant temperature.

The air temperature is the most important of these environmental factors (Auliciems and Szokolay 1997) and for houses that are not excessively damp or draughty is a good measure of the overall physical environment (page 74, Bell, Lowe and Roberts 1996). Air temperatures play a role in the conductive, convective and evaporate heat loss processes of the body. Air temperatures can be measured with a number of different types of thermometers. However a thermometer will also respond to the radiant temperature as well as the temperature of the air.

Air movement, which is usually measured as the mean air speed, affects the convective and evaporative heat loss processes of a person. Higher air movement increases the rate of heat loss due to these processes. Air speeds are measured with a hot bulb anemometer, which relates the heat loss of a heated sphere to the speed of air movement around the sphere.

The rate of evaporative heat loss also depends on the moisture content of the air. A number of different measures can be taken for the moisture content of the air. A common measure is the relative humidity. There are also a number of different ways to measure the air humidity.

Radiative heat transfer occurs between a person and the surrounding surfaces. The amount of heat radiated by a surface is dependent on the fourth power of the absolute temperature of that surface. Rather than measuring the temperature of all the surfaces in view of a person, integrated measurements of the radiant field are frequently used. For example, the mean radiant temperature is a commonly used integrated measurement of the radiant field. The mean radiant temperature is defined as the solid-angle-weighted temperature of surrounding surfaces (Auliciems and Szokolay 1997); another definition is the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the person is the same as the radiant heat transfer for the actual enclosure (ISO 7726 1985). The mean radiant temperature is frequently inferred from the measurements of the temperature at the centre of a black globe (the globe temperature). The mean radiant temperature is related to the globe temperature but depends on the size of the globe used and the air speed around the globe. Measurements of the mean radiant temperature generally suffer from poor accuracy.

2.3.3 Contributing Factors

Other factors can influence the acceptability of particular metabolic rates, clothing levels and environmental conditions. These contributing factors include the intake of food and drink, body shape and in particular the amount of subcutaneous fat, the age and gender of the person and the acclimatization (Auliciems and Szokolay 1997) of the person to changes in their environment both on a short and long-term basis.

2.3.4 Heat Balance

In order to establish the range of environmental and personal factors that give rise to acceptable conditions, a number of experiments have been undertaken in carefully controlled laboratory climate-chambers. In these climate chambers individuals are subjected to a range of conditions and asked to response on the acceptability of the thermal environment. These responses frequently make use of subjective scales of thermal sensation (McItyre 1980). Two commonly used scales are the ASHRAE scale and the Bedford scale, which are shown in Table 2.2.

Table 2.2 ASHRAE and Bedford scales of thermal sensation

ASHRAE Scale		Bedford Scale
Hot	+3	Much too warm
Warm	+2	Too warm
Slightly warm	+1	Comfortably warm
Neutral	0	Comfortable
Slightly cool	-1	Comfortably cool
Cool	-2	Too cool
Cold	-3	Much too cool

The values taken as acceptable for these scales are +1,0 and –1. The two scales report similar values. However there are some reports (Oseland and Humphreys 1994) that the ASHRAE scale has been seen to be bimodal with some respondents attributed the 'warm' category as a pleasant condition where it is intended to represent an unpleasantly warm condition. The two scales neglect responses to humidity and air movement (Auliciems and Szokolay 1997). Comments such as 'dank' for cool-humid conditions and 'muggy' for warm-humid conditions could be used for humidity interactions. Air movement relates to perceptions of the freshness of the air. Lack of air movement can be described as 'stuffy' conditions.

The thermoregulation system of the human body attempts to the keep the core body temperature at a constant value. This constant temperature equates to a certain level of heat storage within the human body. If too much heat is being lost from the body, the thermoregulation system of the human body is capable of making some physiological adjustments – the blood flow to the skin is reduced and if this is not sufficient then shivering may take place. On the other hand if not enough heat is lost from the body then an increase in the blood flow to the skin will occur and then an increase in the degree of sweating from the sweat glands.

It is the contention of the thermal comfort standards, ISO 7730 (ISO 1994) and ASHRAE Standard 55 (ASHRAE 1992), that the lack of thermal stress on a person is equivalent to that person feeling comfortable. The comfort standards therefore make use of thermal balance equations. Two models of thermal balance equations are of general use today; one is the 'two-node model' of the J B Pierce Laboratories (Gagge 1986) and the other is the 'comfort equation' developed by Fanger (1971). The two-node model is used in ASHRAE-55 whereas Fanger's comfort equation is used in ISO 7730.

ASHRAE-55 uses a term derived from the two node model called the New Effective Temperature, ET*, which is a combination of particular environmental and personal factors. The New Effective

Temperature is defined as the temperature of a uniform enclosure at 50% relative humidity, which would produced the same net heat exchange by radiation, convection and evaporation as the environment in question. Climate chamber studies have shown that constant values of the New Effective Temperature are reported as conditions of equal comfort.

ISO 7730 makes use of the Predicted Mean Vote (PMV), which like the New Effective Temperature, is defined in terms of the environmental and personal factors. PMV represents the expected mean ASHRAE comfort vote of a large number of people subject to the same environmental conditions. The Predicted Percentage Dissatisfied is a function of the Predicted Mean Vote and gives the number of people likely to be dissatisfied (scoring outside of +1, 0, -1) with the present environment. It must be recognised that comfort is an individual sensation and even when the environment has a Predicted Mean Vote (PMV) of 0, the Predicted Percentage Dissatisfied (PPD) is 5%.

2.3.5 Reasons for Discomfort

ISO 7730 and ASHRAE 55 also provide ranges of the individual environmental factors that cause discomfort. This section will briefly discuss these factors.

Draughts are a widely recognised cause of discomfort. Draughts increase localised cooling due to high local air speeds. Air speeds of less than 0.25 $m \cdot s^{-1}$ over the whole body did not change the thermal acceptability of the environment (page 8.13 ASHRAE 1997).

The thermal radiation field is directional. Surrounding objects can be appreciably hotter (ceiling mounted radiant heaters) or cooler (large windows) than other objects. The radiant heat exchange between a person and the environment also depends on the person’s alignment with the environment (whether the person is standing or sitting). The result is that asymmetry in the radiant temperature field, depending on it’s direction, can cause discomfort.

The surface temperature of the floor can also cause discomfort due to the direct contact of the occupant with the floor. The degree of discomfort experienced is not only related to the temperature of the floor by also on its thermal conductivity, cold concrete floors are less acceptable than a timber floor at the same temperature due to increased conduction heat loss.

The rate of change of the temperatures may cause discomfort. Oseland and Humphreys (1994) report on studies of thermal responses to slow drifts in the uniform temperature of an environment. It was seen that changes in temperature of less that 0.6°C per hour resulting in no changes in thermal response.

Another cause of discomfort is due to the presence of large vertical temperature gradients. Experiments (Olesen, Schøler and Fanger, 1979) have examined the acceptably of the thermal environment for seated individuals subject to different temperatures at ankle (0.1 m) and head height (1.1 m).

2.3.6 Comfort Field Studies and Adaptability

The PMV and ET* thermal indices, used in ISO 7730 and ASHRAE 55, were derived using thermal sensation responses from individuals in climate chamber experiments. The conditions within the climate chambers are carefully measured and the clothing and activity levels of the individuals recorded. The individuals in these experiments are generally passive in that their roles are generally limited to subjective assessment on the thermal acceptability of some aspects of the environment.

Field studies of comfort involve the typical occupants of real buildings, undertaking regular tasks. Measurements are made of the environmental factors encountered by the occupants and estimates are made of the occupant's clothing and activity levels. The occupants are also asked to record their thermal sensation vote.

The PMV and ET* indices are calculated from the measurements gathered in the field study and prediction made about the comfort of each occupant. These predicted values can be compared to the recorded thermal sensation votes of the occupants. When this is done, inconsistencies frequently appear between what is predicted with the indices and what is actually reported by the occupants (Schiller 1990).

The differences between predicted and reported field study measures of comfort are not yet understood. It is known that people adapt to the environment they are in and make behavioural changes such as putting on more clothes, turning the heater on, or moving to a different environment, when subject to discomfort. (de Dear, Brager and Cooper 1997). It may be that given the opportunity to adapt, people are more accepting of a wider range of thermal environments. Additional field studies of thermal comfort would be of use to better understand the process of adaptability.

2.4 Monitoring Indoor Conditions

The indoor conditions encountered within a building are dependent on both the building and its occupants. The indoor conditions in a collection of buildings (the New Zealand housing stock) can be examined in a number of ways. Lutzenhiser (1992) recognised that models of energy usage in buildings (which is related to the models of the indoor conditions within buildings) could draw on physical engineering, economic, psychological or sociological approaches.

Physical models of the heat flows within buildings are complex, needing to take account of many heat transfer processes. Many of these processes are due to the behaviour of the occupants and their relationship with the indoor environment. Examples of the areas of poor understanding are: when space heaters are used, to what level the building is heated, when people are present within the building and how many windows people leave open. These occupant interactions affect the indoor conditions and as Stoops (1998) implied by the statement "people are not noise", occupant variation is a factor, not a source of error.

The economic, psychological and sociological approaches to the indoor climate in buildings are more focused on the role of the individual. Lutzenhiser (1992) suggests that the economic approach is weakened by the fact that occupants frequently do not behave in an economically rational way. Sociological approaches frequently include many of the important psychological ideas of the occupants' attitudes and beliefs and provide a good perspective on the behaviour of groups of people. Both social groups and indoor conditions need to be defined. Questions such as, *"Do poor people have colder houses?"* require assessment of both 'poor' social groups and 'cold' indoor physical conditions.

There are a wide variety of the social variables that may be of importance when considering the indoor conditions. The main means of gathering this data is the use of surveys of the occupants of the buildings. A social survey may ask questions to determine

- The demographics of the household (such as the age, gender, ethnicity, education, income and number of members of the household)

- The attitudes of the occupants (such as concerns for comfort and health, the need to conserve energy and the effort required to save energy)

- The behaviours of the occupants (such as how often they are home, how frequently they use heaters and how many windows they usually leave open).

As the number of social variables of interest is quite high, many buildings need to be considered to establish relationships amongst the many social and physical variables.

While it is desirable to measure as many physical properties as possible about the indoor conditions in each building, limited funding means that the more intensive the measurements (cost) in each house, the fewer houses that can be considered in total. Including many pieces of experimental equipment for a long period of time within a building also reduces the likelihood of the occupants taking part in the experiment. As the social variations are not well known, and these are best explored through the use of a large number of houses, it was decided to limit the extent of measurements collected from each house to a good understanding of the most important parameter.

The most important measure of the indoor conditions is the indoor air temperature. The indoor temperature is fundamental to the understanding of energy usage in buildings and is a major determinant in occupant health and comfort. The indoor temperature can be measured without too much complication and measurements are comparatively accurate. It also has the advantage over other measures (such as the globe temperature or ET*) in that people can easily relate to it. The methods to measure the indoor temperature are further discussed in Chapter 3.

This thesis will look at the methods required to gather measurements of the indoor temperatures of buildings necessary for a physical-social analysis of indoor conditions. It will examine sources of variation in the measurement of indoor temperatures and will look to account for the large, predictable sources of variation.

The next section will provide an overview of the Household Energy End-Use Project (HEEP), a current source of data on the indoor temperatures in New Zealand houses, and is followed by a description of the approach used for this thesis to provide information on the indoor temperatures of New Zealand buildings.

2.4.1 The Household Energy End-Use Project (HEEP)

Indoor temperature measurements usually form part of a larger data collection exercise, which could include such areas as building performance, energy conservation and occupant health and comfort.

The Household Energy End-Use Project (HEEP) (Stoecklein *et al.* 1997a, 1997b, 1997c, 1998a, 1998b, Bishop *et al.* 1998, Camilleri *et al.* 1999, 2000) is a major research activity to create a rigorous and up-to-date knowledge base of energy use and end-uses in New Zealand residential buildings. HEEP looks to create a predictive model of residential energy consumption (of such types as electricity, gas, LPG and solid fuel) down to an end-use level (such as heating, domestic hot water and lighting), based on both physical (such as house size, insulation levels and climate) and occupant (such as age, gender and household income) parameters.

As space heating is a major component of the energy used in New Zealand houses, and is physically interrelated with the indoor temperatures (see Section 2.1), HEEP also measures the indoor temperatures in each monitored house.

The underlying drivers of energy use and indoor temperatures are not well known so selecting a sample of houses representative of the houses in New Zealand is difficult. To provide the most representative statistics possible, the HEEP sample is based upon a random sample of four hundred houses throughout New Zealand (see Section 3.3, Bishop *et al*. 1998). While it would be convenient to monitor all four hundred houses at the same time, the limited amount of monitoring equipment means that the equipment needs to 'rotated' from year-to-year. Table 2.3 gives an outline of the HEEP monitoring to date.

In addition to the randomly selected houses, a number of houses have also been measured to consider questions of special interest. Initial pilot work was undertaken in Wanganui, where one of these special samples is the 'detailed temperature sample' of nine houses (five houses from wr3 and four houses from wr4) where the indoor temperatures were more extensively recorded at between eight to ten measurement points within each house as compared to the standard three points for the main HEEP sample. This special sample is examined later in this thesis.

Table 2.3 Details of the HEEP samples monitored to date.

Sample(Code)	Selection Method	Type	Location	Number of Houses	Approximate Monitored Period	Temps per house
WR1	Special	End-use	Wanganui	5	25 Apr 96 – 14 July 96	2-3
WR2	Special	End-use	Wanganui	5	18 July 96 – 26 Jan 97	2-3
WR3	Special	End-use	Wanganui	8	19 Mar 97 – 20 July 97	4-10
WR4	Special	End-use	Wanganui	11†	22 July 97 – 25 Jan 98	4-10
XR1	Special	End-use	Wellington	11	1998	6-7
XR2	Random	End-use	Wellington	~ 11	1999	3
	Random	Total	Wellington	~31	1999	1-3
HR1	Random	End-use	Hamilton	11	2000	3
	Random	Total	Hamilton	6	2000	3
	Special	Total	Hamilton	12	2000	2
AR1	Random	End-use	Auckland	5	2001	3
	Random	Total	Auckland	14	2001	3
MR1	Random	End-use	Manukau	3	2001	3
	Random	Total	Manukau	9	2001	3
SR1	Random	End-use	North Shore	2	2001	3
	Random	Total	North Shore	8	2001	3
YR1	Random	End-use	Waitakere	2	2001	3
	Random	Total	Waitakere	5	2001	3

† One of the houses included in the sample for WR4 was also measured in WR1.

In addition to the regular measurements of energy use within each of the households, approximately 600 items of socio-demographic and physical information are also collected. The survey used for HEEP was developed from the socio-demographic survey used by Fitzgerald (Fitzgerald and Ryan 1996) in the monitoring of the electricity usage of a number of Christchurch households.

The survey includes information such as background census information (age, ethnicity, education, employment situation, etc.) on each occupant as well as tables giving their attitudes towards energy, their behaviours that relate to energy use (when they get up and go to bed, how long they take in the shower, etc.), as well as data on their previous usage of energy (energy billing records).

The surveyed physical information about the house quantifies aspects of the building design such as size, construction details, insulation levels, orientation, ventilation and moisture. The appliance information categorises the manner in which energy is used within the household. Details of the methods of heating the house and the manner of hot water heating are included, as are details of the other major energy uses within the house. Limited details on the smaller energy consuming appliances found in each house are also collected.

2.4.2 Methods to Characterise the Indoor Temperature Within Buildings

Understanding a temperature measurement from a house requires an understanding of what variables influence the measured value. As many sources of variation of the indoor temperatures are not known, exploratory analysis will form an important part of this study. Variations can be either predictable from physical properties or non-predictable due to the complexity of the system under investigation. The experimental approach for this thesis will look to determine as much of the predictive variation in the indoor temperatures as possible by limiting the degree of variation present within the data and examining the resulting measurements.

The first source of variance examined for this thesis is from the output of the temperature monitoring equipment itself. Chapter 3 will describe the three types of temperature data logger used to collect data for this thesis and will examine their accuracies.

Indoor temperatures are dynamic so the timing of a measurement will be important. The time response of the temperature measurements undertaken for this thesis will be examined in Chapter 3. Additionally Chapter 4 will examine seasonal, weekly and daily patterns present within the various sources of data on indoor temperatures within New Zealand buildings.

Variations in the temperature measured due to changing the location of the temperature sensor within the living room of a residential building will be examined in Chapter 5. This chapter will form the core of the work undertaken for this thesis.

Chapter 6 will look to extend the information gathered in Chapter 5 by considering the measurements of the indoor temperatures within All Saints Church (Palmerston North) as an example of a room of greater volume and different usage than the residential living rooms examined in Chapter 5.

The analysis for this thesis will be concluded with Chapter 7 making a brief introduction to the temperature variations between the rooms in residential houses before Chapter 8 summarises the conclusions on the measurement of indoor temperatures within New Zealand buildings.

Chapter 3

Measuring Indoor Temperatures

This chapter discusses details of the instrumentation used to measure indoor temperatures. There are a number of different ways to measure temperatures such as liquid-in-glass thermometers, Platinum resistance thermometers, thermistors, thermocouples and integrated circuit (digital) thermometers. With the large amount of data arising from the frequent collection of the indoor air temperature over the course of weeks or months, the use of data loggers becomes essential.

3.1 Data Loggers

A data logger is a self-contained device that automatically collects data and stores it for later retrieval. While it is possible to construct analog data loggers, most modern data loggers are digital and only digital data loggers will be considered here.

A Digital data logger is based around a microprocessor. Data that has been collected is stored in memory within the data logger by the microprocessor. The microprocessor can be interrogated, usually by a computer connected to the data logger (either directly or via a modem), to retrieve the stored data.

Microprocessors work on digital data so data collected and passed to the microprocessor for storage must be digital. Signal processing circuitry is commonly required to produce digital signals from the output of the transducer measuring the physical quantity under investigation. It is common for transducers to produce a voltage output that can be converted to a digital signal by the use of an analog to digital converter.

Some measurement methods are more readily suited for use with data loggers than others. For example, liquid-in-glass thermometers require extensive use of transducers and signal processing circuitry to convert the temperature into a digital signal whereas an integrated circuit thermometer (such as the Dallas DS1624S) subject to a particular temperature has an immediate digital output signal and therefore requires no signal processing.

The flexibility of a data logger can be increased by allowing a number of different transducers to be interchanged and connected to data logger. This is usually achieved by creating a connectable sensor, incorporating the transducer and some signal processing circuitry, separate from the remaining data logger. The input to the data logger (the output of the sensor) may still require signal processing before the data can be processed by the microprocessor. It is also possible to construct the data logger to have a number of input channels so that a number of sensors can be connected to the data logger at the same time.

Data loggers are complicated devices requiring sampling, control and storage capabilities. The development of data loggers has greatly benefited from advances in integrated circuits. Previously data loggers have been bulky and expensive due to the need for complicated circuit design and the use of many, expensive integrated circuit components. Regardless of how many input channels a data logger has, there is a requirement to have a certain amount of core circuitry for control and storage of the data. Adding additional input channels brings down the overall cost per channel of the logger and consequently data loggers were frequently multi-channel devices. With the development of cheap, powerful microprocessors and integrated circuits, the control and storage circuitry for data loggers has been greatly simplified resulting is savings in size and cost for modern day data loggers. Small, cheap single channel data loggers are now common.

3.2 Use of Data Loggers to Measure Indoor Temperatures

To measure a number of temperatures at specific points within a building, then either a multi channel data logger connected by cables to temperature sensors located at these points, or a number of separate single channel temperature loggers, each located at one of these measurement points, is required. Both of these methods have practical advantages and disadvantages for the occupants of the building, the installation of the data loggers, the manner of data collection as well as reliability of the data, some of which will now be considered.

About 30% of randomly selected households approached choose to take part in the Household Energy End-Use Project (see Section 2.4.1) and its incorporated temperature-monitoring programme (Stoecklein, et al. 2000, Camilleri, et al. 1999). A consideration for many occupants asked to take part in the study is how intrusive the data logging equipment will be. Long lengths of exposed cabling, the large physical size of the equipment and the need to use fasteners to attach equipment within the house are some of the detractors. Some reasons to minimise cabling are more unusual; a householder recently approached was happy to take part in the study but asked that the cables not be exposed as their pet rabbit that had a tendency to nibble cables.

The extensive use of cabling also adds to the amount of time needed to install the data loggers and can compromise the placement of sensors. For example, for the measurement of electricity usage in a house, it is convenient to place sensors and data loggers to measure the electricity used in the household on the fuse board for the house. If, in addition, it is desired to record the indoor temperatures with these data loggers then cabling is required from the temperature sensor located in the room where the temperature is being monitored back to the fuse board and the data logger. One way to conceal the cable while avoiding removing wall linings, is to place the temperature sensor on the ceiling close to a light fitting so that the cabling can be run back past the light fitting and through into the roofspace.

A problem with this method is the proximity of the temperature sensor to the light fitting. The temperature reported by the sensor may include effects due to the radiation from the lights. Figure 3.1 shows data from six days of measurements from a real house monitored in this way. It should be noted that the outside temperature has not been correctly monitored but it is believed to have a similar shape to the data shown. From Figure 3.1 it can be seen that the indoor temperature responses to the operation of the heater, but that the indoor temperature also responses in a similar way sometimes when the lights are on but the heater off. It is possible that the measured indoor temperature is also being influenced by the operation of the light near the light sensor but this light is not always on when other lights are on.

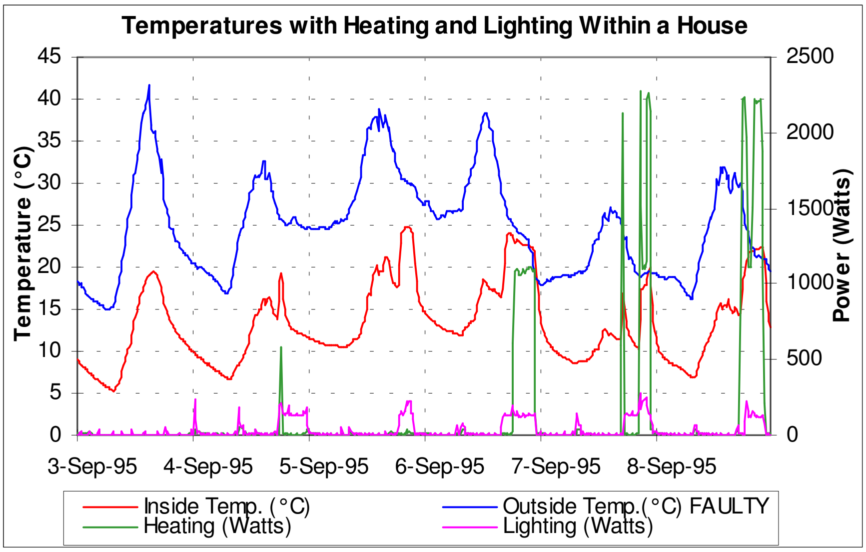


Figure 3.1 The indoor and outdoor temperatures, heating and lighting for a house monitored over six days

It is also possible to reduce cabling by using methods other than dedicated signal cables for communication between the sensor and the data logger such as radio or other wireless methods. A method that is frequently used in electrical logging is to make use of the existing electrical wiring within the building for transferring data between the sensor and the data logger both of which would be connected to the wiring.

Small data loggers with integrated sensors also generate problems. While the small size of the loggers allows them to be easily positioned within the room they can also be unintentionally repositioned by being knocked or by being picked up by small children.

The operation of the data loggers may be noticeable to the occupants. The Tinytag temperature logger (see Section 3.3.1) has a LED installed within it that flashes dimly every four seconds to indicate that the data logger is collecting data. When a Tinytag temperature logger was placed in a bedroom in a house in Wanganui (a house that was part of the HEEP detailed temperature dataset) the occupant noticed the flashing LED and placed a piece of paper over the LED. While this did not affect the measurements other potential occupant interactions are more important. In Australia, when a large household energy measurement programme was undertaken, a selection of individual appliances (such as TVs and clothes dryers) were monitored by installing a sensor between the appliance's 3-pin plug and the wall socket. Unfortunately when used with a TV this energy sensor had a tendency to interfere with the TV reception so that people were inclined to bypass the energy sensor and plug the TV straight into the wall socket so that data was not always collected on TV energy consumption (Bartels 1998).

Data collection is made easier by reducing the number of data loggers installed within each building. Currently HEEP makes use of monthly 'download' visits to each monitored building. A laptop computer is used to connect to and transfer data between each data logger and the laptop computer. These regular visits to the houses are also useful to correct problems with the data loggers, to reposition data loggers that have been accidentally moved, to move energy consumption sensors to monitor different appliances within the house and to maintain good relations with the occupants.

Download visits become increasingly more awkward when the sample of houses is more geographically remote. HEEP is planning to trial a procedure where the occupants are sent the data loggers by mail to be interchanged with the data loggers currently installed within the house, which are then returned by mail so the data from them can be downloaded. The practicalities of this procedure have yet to be fully investigated.

Some data loggers are capable of being used with modems to allow them to be remotely downloaded and programmed. When all the data from a particular building is capable of being remotely downloaded (perhaps with the use of a central multi-channel data logger) then timesavings can be made by reducing the need to regularly visit the monitored buildings. Using modems however does introduce a greater degree of cost and complexity into the collection of data. Modems require a phone line. Adding an additional phone line to a building for the modem adds to the installation costs of the data logging equipment. Additionally the line would only be used infrequently so that the fixed line charge for the phone line would be high in comparison to the cost of transferring the data. An alternate option is to use a prepaid cell phone, which would reduce installation costs and as these services charge only for the time used for data transfer the overall cost may be lower. The use of cell phones is restricted to those buildings that are in an area of cell phone coverage. Another option is to share the existing phone line (if such a line is present) with the occupants. A problem with this method is the phone line being in use when it is desired to transfer data. Dialling-into a data logger may be difficult due to the occupants or other devices (answer phones, fax machines, computer modems) answering the call before the data logger. Having the data logger automatically dial-out to the downloading computer also has the problem that the data logger must have a method (redial algorithms) to deal with the phone line being busy or being interrupted during the connection. If a connection to the data logger can not be established then a physical visit to the data logger may be required. If the data transfer call is a chargeable call (toll call) then the cost of the call will be charged to the occupants, which adds to the inconvenience the data logging has on the occupants

Data loggers are reliable devices but problems with them do occur. Data loggers operate over an extended time and the microprocessor controlling them can develop a fault. A faulty microprocessor can cause the data logger to not function correctly and may require resetting before it will operate correctly again. Resetting a data logger is usually carried out by the removal and replacement of the battery (or power supply) to the microprocessor. Depending on the design of the data logger, resetting the data logger may or may not lose the data already collected by the data logger. In the interests of data reliability data loggers should not be left too long before they are downloaded. If the loggers use batteries, it is necessary to ensure that the battery has enough remaining capacity to collect data until the logger is next offloaded. Having the measurement tasks shared by a number of data loggers also means that if a data logger has a problem then not all of the data from that building is lost.

3.3 Properties of the Temperature Loggers Used

The analysis undertaken in this thesis used data collected from three types of temperature loggers: the Tinytag Temperature Logger, a single channel logger which has a thermistor as the temperature sensing element, the single channelled BRANZ Temperature Logger which uses the Dallas Semiconductor DS1624S digital thermometer and the BRANZ Microvolt Logger, a four-channel thermocouple logger with each thermocouple sharing a common reference junction. The temperature of this reference junction is measured using the DS1624S digital thermometer. Each of these types of data loggers will be briefly considered in the follow sections.

3.3.1 Tinytag Temperature Logger

The Tinytag Temperature Loggers have been used extensively by BRANZ to measure the indoor temperatures in a number of residential buildings for the Household Energy End-Use Project (HEEP) project. The Tinytag is manufactured by Gemini Data Loggers in the UK and is a very compact logger being enclosed in a standard 35 mm film canister (54 mm by 32 mm diameter). A picture of a Tinytag logger is shown in Figure 3.2.

Figure 3.2 Tinytag Temperature Logger

The Tinytag loggers record an instantaneous temperature measurement at an adjustable recording interval of between one second and ten days. The Tinytag uses a Microchip PIC 16LC58 microprocessor with 8kB of EEPROM data storage. This memory provides approximately 82 days capacity for fifteen-minute data or about 5 days capacity for one-minute data.

The principle of operation of the Tinytag logger is to record the response of a 10k NTC thermistor. The voltage across the thermistor is measured using an 8-bit analog to digital converter. For a thermistor, the absolute temperature, T, and the electrical resistance, R, can be approximately related by the Steinhart-Hart equation (Steinhart and Hart 1968, Schooley 1986, Potter 1996)

$$\frac{1}{T} = a + b(\ln R) + c(\ln R)^3 \tag{3.1}$$

where *a, b* and *c* are constants dependent on the thermistor used. For the Tinytag Logger the constants are given in Table 3.1

Table 3.1 Coefficients in the Steinhart-Hart equation for the thermistor used in the Tinytag loggers.

Constant	**Value**
a	1.028×10^{-3}
b	2.392×10^{-4}
c	1.562×10^{-7}

As it is the voltage drop across the thermistor that is being digitised (rather than the temperature), the temperature resolution of the logger is not constant with temperature. Two types of Tinytag loggers are being used by BRANZ; one is the General Range Tinytag which has a temperature range of -40°C to 75°C and the other is the Environmental Range Tinytag which has a temperature range of -10°C to +40°C. These loggers use the same thermistor but differ in the voltage range settings for the analog to digital converter. The improved precision of the Environmental Range Tinytag ('E' range) over the General Range Tinytag ('G' range) comes from sampling a narrower range of voltage. The temperature resolution for both loggers over the temperature range of 0°C to 40°C is shown graphically in Figure 3.3

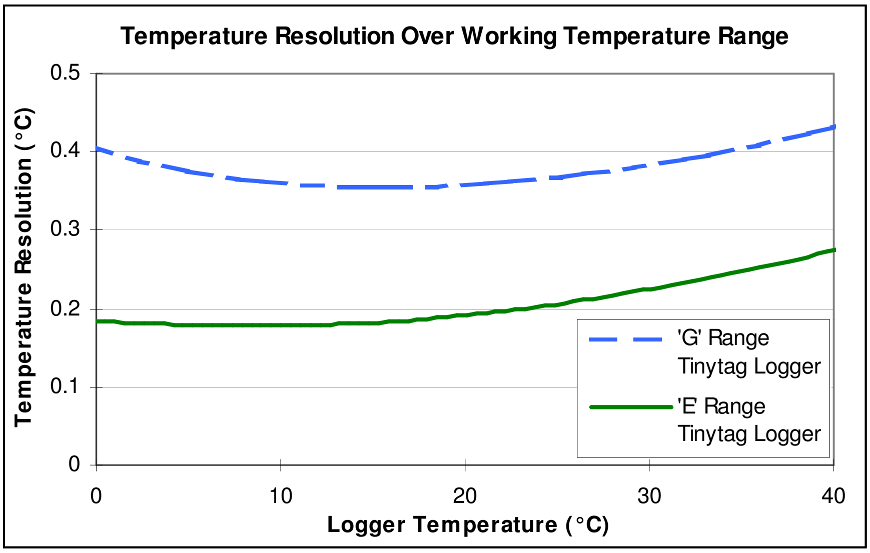


Figure 3.3 Temperature resolution of the Tinytag Temperature Loggers

3.3.2 BRANZ Temperature Logger

The BRANZ Temperature Logger (shown in Figure 3.4) is a low cost, compact (90 mm by 60 mm by 25 mm) temperature logger. Instantaneous temperature readings are made at one of the preset logging intervals which include one, two, five, ten and fifteen minute intervals. The memory of the logger allows for the storage of approximately 300 days of fifteen-minute data.

Figure 3.4 A BRANZ Temperature Logger with a Tinytag Temperature Logger

The hardware of the BRANZ Temperature Logger consists of a Microchip PIC 16C76 Microprocessor, 64kB of serial memory along with a DS1624S digital thermometer made by Dallas Semiconductor. The DS1624S (Dallas Semiconductor 1998) provides temperature measurement in a single integrated circuit that can be directly interrogated by the PIC microprocessor. The method used by the DS1624S to determine the temperature involves the comparison of two oscillators. The frequency of one oscillator has a high temperature dependence while the frequency of the other oscillator has a low temperature dependence. Counters are employed for both oscillators. The temperature is derived from the number of counts of the highly temperature dependent oscillator for a fixed number of counts of the low temperature dependence oscillator. The temperatures are recorded by the DS1624S with a resolution of 0.03125°C. A 13-bit format is used for data storage, however, not all of this capacity is utilized with recordings restricted to a temperature range of -55°C to +125°C.

Samples of BRANZ Temperature Loggers were calibrated on three separate occasions with a total of 42 separate loggers being calibrated. Five loggers were calibrated twice. For each logger a linear function was fitted between the output of the Temperature Logger and the reference temperature (a calibration curve). Figure 3.5 and Figure 3.6 give histograms of the slopes and intercepts (respectively) of these functions. Figure 3.5 shows that the slopes of each of the calibration curves are clustered and are close to 1. Figure 3.6 shows that the intercept term is somewhat spread out with a mean value of approximately 0.7°C and a standard deviation also approximately 0.7°C. As this intercept term has a moderate degree of variation, operating the logger without a calibration correction will result in sizeable errors, therefore a linear calibration correction is applied to the output of each Temperature Logger. This calibration correction is stored within the program memory of the Temperature Logger and is applied to the data when it is transferred from the memory of the logger (where it is stored as uncalibrated data) to a computer.

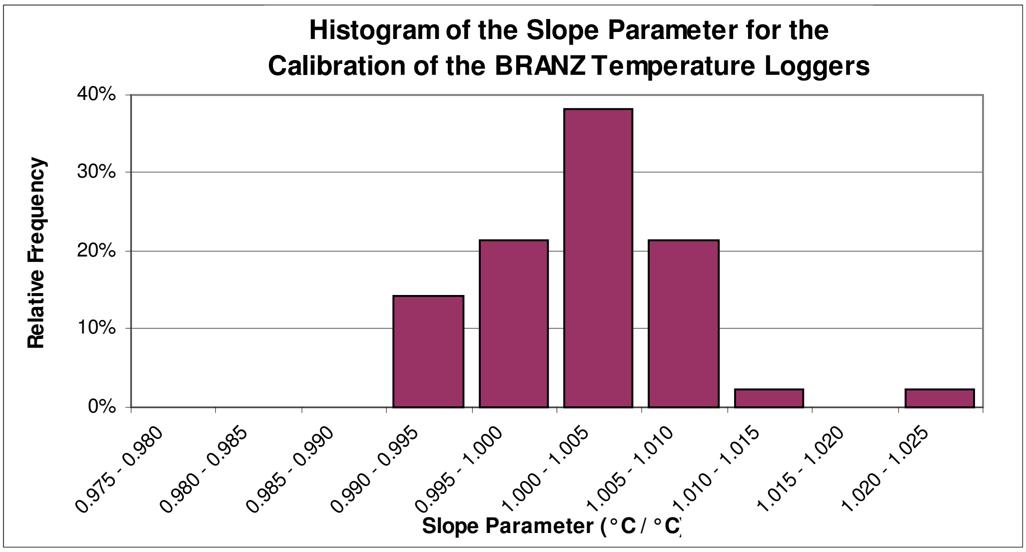


Figure 3.5 Histogram of the slope parameter of the fitted linear function of the calibration of the BRANZ Temperature Loggers.

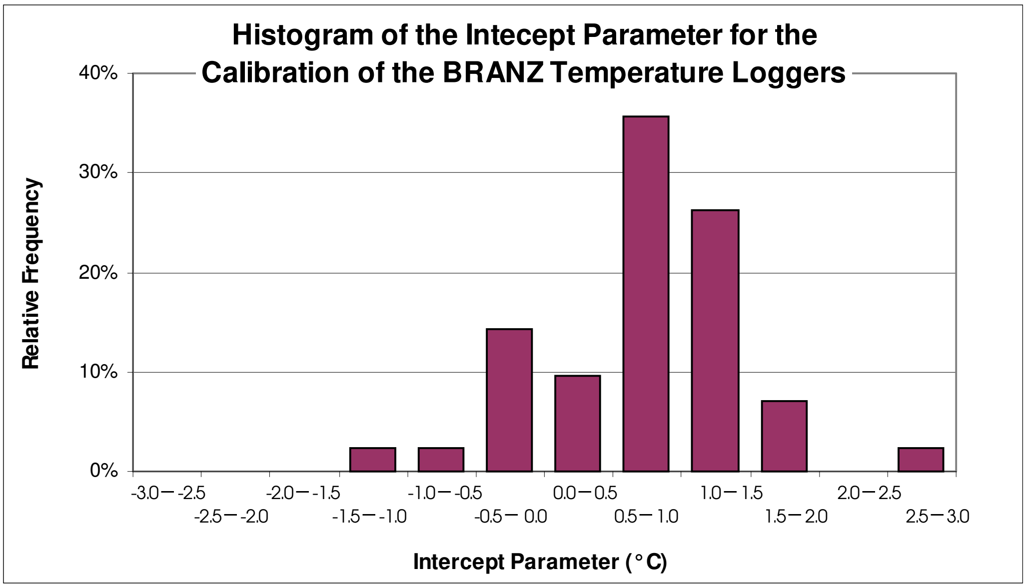


Figure 3.6 Histogram of the intercept parameter of the fitted linear function of the calibration of the BRANZ Temperature Loggers.

3.3.3 BRANZ Microvolt Logger

Figure 3.7 BRANZ Microvolt Logger

The logger used to record the indoor temperature in All Saints Church in Palmerston North was a prototype BRANZ Microvolt Logger (Flanagan, 1998). This logger was developed at BRANZ by Sean Flanagan and Ian Cox-Smith. During the period of logging in All Saints Church, the logger under went a number of software modifications but the hardware remained the same.

The BRANZ Microvolt Logger (shown in Figure 3.7) is a voltage logger that uses the same case as the BRANZ Temperature Logger. The Microvolt Logger includes amplification circuitry to allow for microvolt level signals to be recorded. This microvolt level input allows the Seebeck voltage of a thermocouple to be measured directly by connecting the thermocouple wire to the input of the logger. The reference junctions of the four thermocouple inputs are in isothermal contact and their temperature is measured using a DS1624S digital thermometer as used in the BRANZ Temperature Logger.

A block diagram of the Microvolt Logger is shown in Figure 3.8. The Microvolt Logger is controlled by a Microchip PIC 16C76 microprocessor chip and includes 64kB of serial EEPROM memory for data storage. The recordings made are instantaneous readings of the inputs at the boundary of one of the preset logging intervals, which include one, two, five and fifteen minute intervals. The memory of the logger provides for approximately 77 days of storage of fifteen-minute data or approximately five days of storage when used with a one-minute recording rate.

The four-channel microvolt inputs of the Microvolt Logger(between –2000 μV and 3000 μV) are offset (by approximately 2000 μV) before being amplified (with a gain of 1000) by a Maxim MXL1179 quad operational amplifier. The op-amp output then undergoes a 12-bit analog to digital conversion (over the 0 – 5 V range) using a Linear Technology LTC1594 chip. The digital output is then subject to microprocessor control with measurements stored in memory before being transferred to a computer.

The microprocessor in the Microvolt Logger contains two calibration correction algorithms. One algorithm (identical to that in the Temperature Logger) is to correct the temperature reported by the DS1624S digital thermometer. The other algorithm adds individual correction factors to the four voltage outputs of the Microvolt Logger for the variation of the offsets with temperature. The temperature used for this offset correction is taken as the corrected reference junction temperature as measured with the DS1624S subject to its calibration correction.

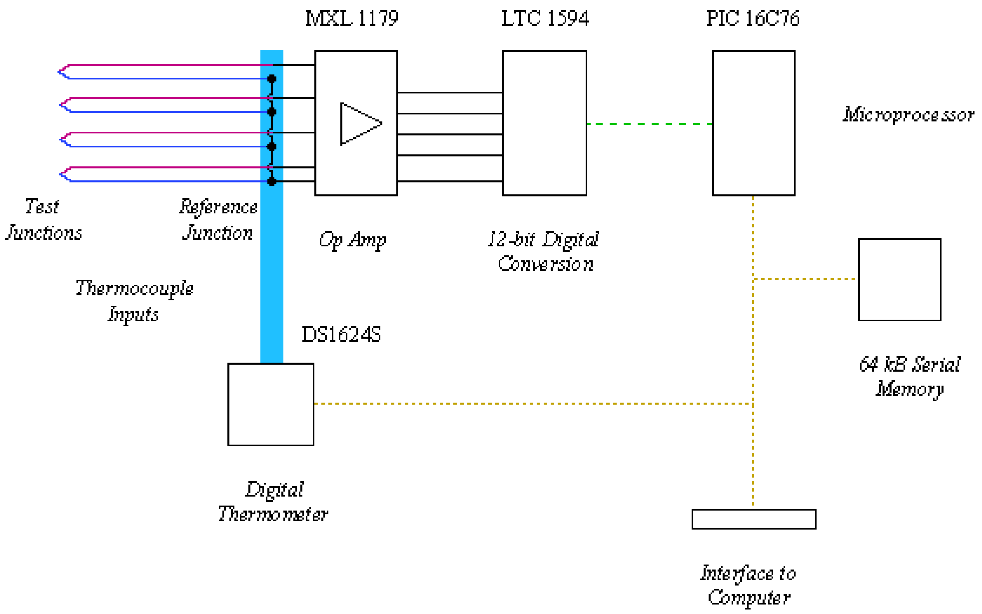


Figure 3.8 Block diagram of the Microvolt Logger

3.3.4 Thermocouple Wire

The thermocouple wire used with the Microvolt Logger was from a spool of T-type (copper/copper-nickel alloy) thermocouple wire manufactured by Claude S Gordon Company. This spool was calibrated by the Measurements Standards Laboratory at Industrial Research Limited (IRL, 1992) over a range of 0°C to 100°C. The calibration gives the resulting thermocouple potential for the given temperature of the test junction while the reference junction is maintained at 0°C. A third-order polynomial can be used to describe the reference junction temperature as follows

$$T = a_0 + a_1 V + a_2 V^2 + a_3 V^3 \tag{3.2}$$

where T is the test junction temperature (in Celsius), V is the potential produced by the thermocouple (the Seebeck voltage, measured in Volts) and a_0, a_1, a_2, and a_3 are coefficients for this particular thermocouple wire and are given in Table 3.2.

Table 3.2 Polynomial coefficients in the calibration equation for the T-type thermocouple.

Coefficient	**Value**
a_0	0
a_1	2.589×10^4 K· V^{-1}
a_2	-7.33×10^5 K· V^{-2}
a_3	3.35×10^7 K· V^{-3}

When the Microvolt Logger is used to record indoor temperatures it is not practical to maintain the reference junction at a fixed temperature. It is necessary to account for the varying potential of the reference junction by inverting Equation (3.2) to express the potential as a function of reference junction temperature (Nicholas and White, 1982:pp 99). This inversion was achieved numerically by fitting a third order polynomial (by least squares) through the sampled data giving the following equation

$$V = b_0 + b_1 T + b_2 T^2 + b_3 T^3 \tag{3.3}$$

where the coefficients of the inverted equation are given in Table 3.3. This reference junction potential is then added to the potential measured by the Microvolt logger between the test junction and the reference junction. This summed potential is then used in Equation (3.2) to give the temperature at the thermocouple test junction.

Table 3.3 Polynomial coefficients in the inverted calibration equation for the T-type thermocouple.

Coefficient	**Value**
b_0	5.00×10^{-7} V
b_1	3.85×10^{-5} V· K^{-1}
b_2	4.62×10^{-8} V· K^{-2}
b_3	3.53×10^{-11} V· K^{-3}

Unlike the Temperature logger or the Tinytag logger, the output of the Microvolt Logger is not immediately available as a temperature but must instead be calculated by the procedure outlined above. With large amounts of data being collected by the Microvolt logger this calculation process is best achieved by automated processing. This was achieved by importing the data into a spreadsheet for processing.

3.4 What the Temperature Loggers Measure

The temperature sensors within the Tinytag temperature logger, the BRANZ temperature logger and the BRANZ Microvolt logger respond to both the air temperature surrounding the logger and the radiant temperature at the temperature sensor. The temperature reported by the temperature sensor will lie between these two values. The case of the data logger surrounding the temperature sensor will play a large role in the radiant temperature seen by the temperature sensor. In order to reduce the effect of radiant temperature upon the data logger's measurement of temperature, the data logger should not be placed in the direct path of light (sunlight or artificial light) or near to any surfaces that are much cooler or warmer than the surrounding air.

3.5 Thermal lag

As the temperature loggers are sampling dynamic temperatures, it is important to understand the response time (thermal lag) of the logger. The thermal lag of the temperature logger can be modelled by a low pass filter response.

Most temperature variations of interest are slowly varying, such as due to the operation of heaters or from solar gains. However draughts are associated with higher frequency air temperature fluctuations, perhaps related to the 0.2-1.2 Hz air temperature fluctuations identified by Melikov *et al.* (1996), and the thermal lag will be important.

The thermal time-constant (in air) of a Microvolt Logger was established by using two constant-climate environments, one set at 5°C, the other at 26°C. The logger was set to a one-minute recording interval and was left to stabilise in the 5°C environment. The logger was then quickly transferred to the 26°C environment (at approximately 16:16 in Figure 3.9).

The response of the reference junction temperature (as measured by the DS1624S) and the test junction temperatures of the thermocouples (calculated using the DS1624S temperature as the reference junction temperature) are shown in Figure 3.9. The reference junction measurement has a slower response than the test junction.

To begin with, the temperature response of the DS1624S (the reference junction thermometer) will be considered.

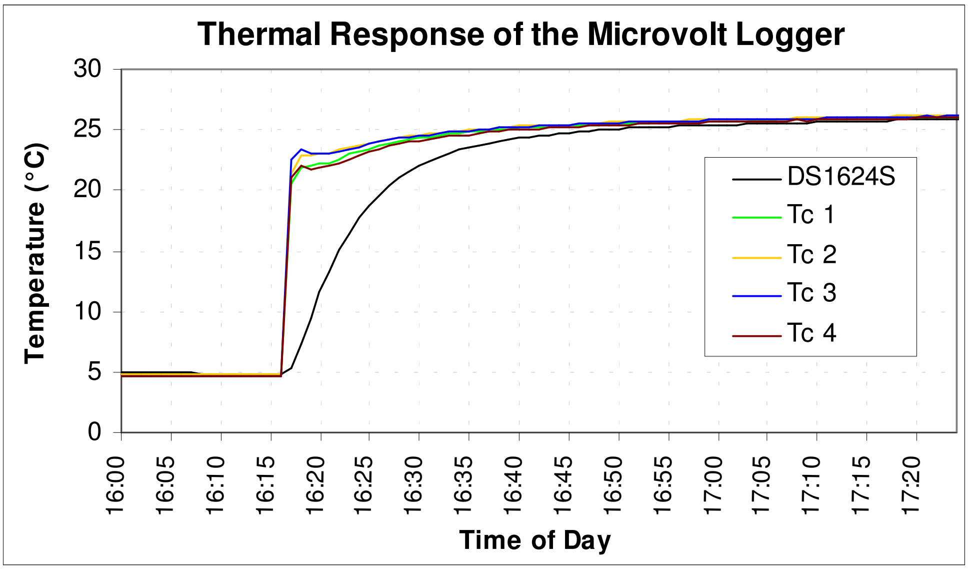


Figure 3.9 Thermal response of the BRANZ Microvolt Logger

To model the thermal lag of the DS1624S reference junction thermometer, an analogy to electrical systems is used with voltage being replaced with temperature. Figure 3.10 shows the model

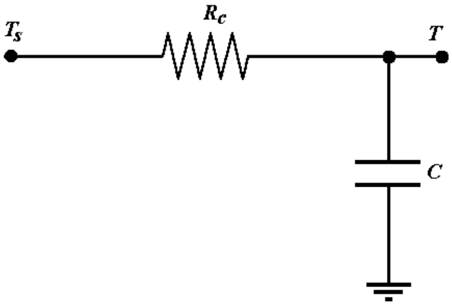


Figure 3.10 Model used for the thermal lag.

diagrammatically, where $T_s = T_s(t)$ is the temperature of the system being measured, R_c is the thermal contact resistance, $T = T(t)$ the temperature recorded by the thermometer and C is the heat capacity of the thermometer. This network problem can be solved with Kirchhoff's laws, which require that

$$T_s(t) = R_c C \frac{\mathrm{d}T(t)}{\mathrm{d}t} + T(t) \tag{3.4}$$

The temperature of the system the logger is exposed to (T_s), is subject to a sudden change of temperature. This can be modelled with the Heaviside step function, $h(t)$, which is defined by

$$h(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \tag{3.5}$$

so taking the change of temperature at $t = 0$ (that is at 16:16), the temperature of the system can be written as

$$T_s(t) = 5 + 21 \cdot h(t) \tag{3.6}$$

Putting equation (3.6) into (3.4) and taking the Laplace Transforms gives a solution for the Transformed variable $U(s) = \mathcal{L}\{T(t)\}$ of

$$U(s) = \frac{\frac{26}{R_c C} + 5s}{s(s + \frac{1}{R_c C})} = \frac{26}{s} + \frac{-21}{s + \frac{1}{R_c C}} \tag{3.7}$$

which when inverse Laplace transformed, gives the temperature measurement for the thermometer after a time t has elapsed of

$$T(t) = 26 - 21e^{\frac{-t}{\tau}} \tag{3.8}$$

where $\tau = R_c C$ is the time constant of the thermal system.

The functional form of equation (3.8) can be used to experimentally determine a value for the time constant. The time constant was initially set to a trial value and was then iteratively adjusted using the ‘goal -seek” function of Excel[*], minimising the differences in the sums of squares between the experimental thermometer temperature measurement and the temperature predicted from equation (3.8) using the current iterative value of the time constant. The iterative process was continued until the next iteration of the time constant was less than one second different from the previous iteration.

The value of the time constant for the DS1624S thermometer temperature measurement of the BRANZ Microvolt Logger was (to two significant figures) 460 seconds (7 minutes 40 seconds). It must be noted that this value is approximate as the contact resistance that is one factor in the time

---

[*] Microsoft Excel for Windows 95 version 7.0.

constant, is dependent on the mixing of the air surrounding the logger and would depend on the air speed close to the logger.

The time response of the test junction are more complex than the time response for the DS1624S thermometer. It was seen in Figure 3.9 that one minute after being exposed to the 26°C environment the test junction temperatures were reading temperatures above 22°C. After fluctuating for about three minutes the test junction temperatures begin to increase towards 26°C in a similar fashion to the DS1624S temperature measurement.

The test junction temperature is calculated from the thermoelectric potential of the thermocouple and the temperature of the reference junction. The time constant for 0.5 mm diameter thermocouple wire is about 1 second (Omega Engineering 2001).

The calculated test junction temperatures do appear (Figure 3.9) to have a thermal lag. This is due to the temperature used in the test junction temperature calculation (the temperature from the DS1624S thermometer) not exactly matching the temperature of the actual reference junction.

A time constant measurement was made on a Tinytag temperature logger in a similar way to that explained for the DS1624S reference junction temperature measurement for the Microvolt Logger. Despite this logger being smaller and with a separate temperature-sensing element, the time constant for the Tinytag logger was 650 seconds (10 minutes 50 seconds), approximately 40% longer than for the Microvolt logger.

The time constant of the BRANZ Temperature Logger is expected to be similar to that of the DS1624S temperature measurement for the Microvolt Logger due to the use of the same temperature sensing element (DS1624S) and similar construction of the logger.

3.6 Temperature Logger Uncertainties

Critical to the measurement of any physical quantity is knowledge of the accuracy of the measurement (ISO 1993). The accuracy (uncertainty) of a temperature logger is how well the temperature logger reproduce temperatures in comparison to the recognised temperature scale (International Temperature Scale, ITS-90).

The uncertainties in this Section are calculated as estimates of the standard deviation of the measurement (ISO 1993). As many of the uncertainties are of similar magnitude the uncertainties are generally shown to higher precision (the uncertainties in the temperature measurements are usually shown rounded to two decimal places) so that the relative importance of the contributing sources of variation can be seen. When uncertainties are calculated and combined the calculations are undertaken to the maximum precision available.

The international standard ISO7726 is concerned with the instruments and methods for measuring the physical properties of the thermal environment ISO7726 requires that air temperature is recorded with an uncertainty of better that 0.5°C with a desired uncertainty of better that 0.2°C.

The reference thermometer used for all of the calibrations of the temperature loggers was a Platinum Resistance Thermometer (PRT) calibrated against ITS-90 by the Measurements Standards Laboratory (IRL 1995) to an expanded uncertainty of 0.025°C at the 95% confidence level. Taking the 95% confidence level as 1.96 times the standard uncertainty gives an approximate standard uncertainty for the PRT of 0.01°C.

The temperature and electrical resistance of a PRT are directly related. The electrical resistance of the reference PRT used was measured with a Hewlett Packard HP34401A Digital Voltmeter (DVM). The calibration of this DVM was such that the resistance measurement of the PRT was equivalent to the temperature measurement being within ±0.04°C (Hearfield and Cox-Smith 1998). A temperature measurement within ±0.04°C is equivalent to a standard uncertainty (standard deviation for a rectangular distribution of half-width $a = 0.04$°C) in the temperature measurement of $\frac{a}{\sqrt{3}} \approx 0.02$°C. The output of the DVM was transmitted by a RS-232 connection to a data acquisition system installed on a laboratory computer.

Overall the combined standard uncertainty (the square root of the squares of the individual standard uncertainties) of the PRT measurement would then be approximately 0.03°C.

The calibration of each logger type was made with the use of a reference environment. This reference environment was set to a number of temperature set-points (5°C, 15°C and 25°C). Once each set-point had been well established, a period of time was allowed so that thirty one-minute recordings would be gathered by the each of the loggers under calibration as well as from the PRT data acquisition system. Appendix C describes the methods used to obtain this environment and notes that the environment was stable to an uncertainty of approximately 0.14°C.

Combining the uncertainties (by taking the square root of the squares of the individual standard uncertainties) of the uncertainty in the stability of the calibration environment (0.14°C) with the uncertainty in the temperature of the calibration environment (0.03°C) gives an uncertainty for the calibration environment of 0.14°C.

In addition to the stability of the calibration environment, the uncertainties in the logger temperature measurement will be seen in the variations between the logger outputs (including any calibration corrections) within the environment. Another source of uncertainty in the temperature measurement for a logger temperature measurement will be from the behaviour of the loggers in a dynamic environment. With slowly varying temperatures and a long sampling period, when compared to the logger's thermal lag (see Section 3.4), this dynamic behaviour can be reduced to the uncertainty due to the temperature resolution of the logger.

The consistency of the logger responses within the calibration environment and the temperature resolutions for each type of logger will be considered in the following three subsections.

3.6.1 BRANZ Temperature Logger

As was described in Section 3.3.2, the output of each Temperature Logger is subject to a linear calibration correction. This correction greatly reduces the errors associated with the temperature measurement. The standard deviation of the temperature differences between the calibration environment and the corrected Temperature Logger output for thirty one-minute readings at each of the temperature set-points was approximately 0.03°C.

If no calibration correction were made to the output of the Temperature Logger the standard deviation of the temperature differences between the calibration environment and the output of each Temperature Logger would be 0.66°C.

The temperature measurements from the DS1624S chip have a resolution of 0.03125°C. Taking this digitisation as a rectangular probability distribution of half-width $a = 0.03125$°C, provides for a standard uncertainty due to the digitisation of approximately 0.02°C.

The combined standard uncertainty (the square root of the sum of the squared standard uncertainties) due to the calibration environment variation, logger variation and the logger resolution was better than 0.2°C with the calibration environment uncertainty being the dominant component in the overall uncertainty of 0.14°C in the temperature measurement from the BRANZ Temperature Logger.

3.6.2 Tinytag Temperature Logger

The manufacturer quotes an uncertainty of 0.2°C for the thermistors used in the Tinytag Temperature Loggers. A calibration run was conducted on 81 General Range Tinytags and 9 Environmental Range Tinytags using the guarded rotatable hotbox (see Appendix C). The calibration was conducted at three temperature set-points of approximately 5°C, 11°C and 21°C.

After each set-point had been reached twenty minutes was allowed for twenty one-minute readings to be gathered from each of the Tinytags.

The residual values between the PRT temperature measurement of the calibration environment and the temperature measurement from each of the Tinytag loggers for all three temperature set-points had a standard deviation of 0.15°C.

The temperature resolution of the Tinytag logger was seen in Figure 3.3 to vary with temperature. The largest spacing for the General Range Tinytag in the 0°C to 40°C range is 0.43°C, which corresponds to a standard uncertainty due to digitisation of about 0.25°C. Similarly the standard uncertainty due to digitisation for the Environmental Range Tinytag (maximum spacing of 0.28°C) is about 0.16°C.

The combined standard uncertainty for the Tinytag Loggers are approximately 0.3°C with the Tinytag 'Environmental' Logger (0.26°C) having a better uncertainty that the Tinytag 'General' Logger (0.32°C). The source of uncertainties for a Tinytag Logger are roughly evenly split between thermistor accuracy, logger resolution and the consistency of the calibration environment.

3.6.3 BRANZ Microvolt Logger

The BRANZ Microvolt Logger record temperatures in two different ways. The reference junction temperature is measured with a Dallas DS1624S digital thermometer in a similar way to the BRANZ Temperature Logger and consequently has an uncertainty of about 0.14°C. The other temperature measurement of the Microvolt Logger is from the voltage measurements for the four channels of T-type thermocouples. There are a number of steps to determine a temperature from the thermocouple output and each of these steps introduces uncertainty in the resulting temperature measurement.

The thermocouple wire was calibrated over the range 0°C to 100°C (IRL 1992), and was found to give temperatures with an expanded uncertainty (2.65 times the standard uncertainty) of 0.3°C at the 99% confidence level, giving a standard uncertainty for the thermocouple wire of approximately 0.11°C.

The uncertainty in the voltage generated by the thermocouple wire, $u(V)$, can be related to the uncertainty in temperature of the thermocouple wire, $u(T)$, by taking (ISO 1993)

$$u^2(T) = \left(\frac{\mathrm{d}T}{\mathrm{d}V}\right)^2 u^2(V) \tag{3.9}$$

where $\left(\frac{\mathrm{d}T}{\mathrm{d}V}\right)$ is the derivative of Equation (3.2) and is evaluated for a particular voltage, V. Equation (3.2) is only valid for temperatures between 0°C and 100°C and within this range $\left(\frac{\mathrm{d}T}{\mathrm{d}V}\right)$ has maximum value of 2.589×10^{-4} K· V^{1} when both T and V are zero. Using this maximum value in Equation (3.9) gives the uncertainty in the voltage from the thermocouples of $u(V) = 4.4$ µV.

A voltage offset of approximately 2000 µV is applied to the output of the thermocouples. The uncertainty in this voltage offset is taken as depending only on the temperature and was determined from examining the output of eight Microvolt Loggers each of which had their inputs grounded. These Microvolt Loggers were subject to five temperature set-points (5°C, 10°C, 15°C, 20°C, 25°C) and sufficient time was allowed at each set-point for twenty one-minute readings to be gathered. The output voltage was seen to have a reasonably linear relationship with the temperature and residual values were calculated for the 32 offsets measured. The uncertainty in the voltage measurement was taken as the standard deviation of these residuals, which had a value of about 0.6 µV.

The behaviour of the gain of the operational amplifiers was also investigated (with no correction applied) for nine Microvolt Loggers. At a temperature of 20°C, the output of the Microvolt Loggers were recorded for twenty one-minute measurements with voltages of 2000 µV, 1000 µV, -1000 µV and -2000 µV applied to the input terminals of the Microvolt Loggers. These voltages were generated with a Fluke 701 Process Calibrator and were measured with a Hewlett Packard HP4401A Digital Voltmeter. The uncertainty of the voltage gain of the op-amp is taken as the square root of the average variance across the nine Microvolt Loggers for the twenty readings at each of the input voltages and had a value of 2.9 µV.

It has been assumed that the uncertainties due to the offset and gain are independent and that the uncertainty due to the offset is dependent on temperature only and that the uncertainty due to the gain is dependent on the input voltage only.

The outputs of the op-amps were digitised for a voltage range of 0 – 5 V to a 12-bit resolution. This corresponds to resolution in the input signal of about 1.2 µV, which has an uncertainty due to digitisation of about 0.7 µV. The output values of the Microvolt Logger are subject to rounding to the nearest microvolt introducing a further uncertainty of 0.3 µV (Taken as a rectangular distribution of 0.5 µV half-width). The combined uncertainty due to digitisation and rounding is 0.8 µV.

Combining the uncertainties due to the thermocouple wire, offset, gain, digitisation and rounding produces an overall uncertainty in the input voltage measurement of 5.4 μV. Using Equation (3.9) to convert this voltage uncertainty back to a temperature uncertainty gives a temperature uncertainty from the thermocouple of 0.14°C. with the largest component of this uncertainty coming from the uncertainty in the thermocouple voltage.

When the thermocouple voltage is used to make an absolute temperature measurement, following the methods outlined in Section 3.3.4, use of both the thermocouple voltage measurement and reference junction temperature is required. The overall uncertainty in the temperature measurement is therefore approximately 0.2°C.

3.7 Closure

Small, self-contained temperature loggers are a practical way to collect indoor temperatures from buildings. Monthly download visits are made to the data loggers to retrieve the data from the loggers and to confirm that the monitoring is being undertaken as envisaged.

The data the temperature loggers record are between the temperature of the air surrounding the logger and the radiant temperature. In order that the radiant temperature does not have too great an effect the temperature loggers should be placed out of path of direct light and not near cold or hot surfaces.

The time constant for the Tinytag Temperature Logger is around eleven minutes and around eight minutes for the DS1624S temperature measurement for the BRANZ Microvolt Logger. Owing to the DS1624S not exactly matching the reference junction temperature, the calculated test junction temperatures (using the DS1624S as the reference temperature) will appear with time lag. The time constant for the BRANZ Temperature Logger is expected to be similar to that of the DS1624S for the BRANZ Microvolt Logger.

The Tinytag Temperature Logger had an accuracy of approximately 0.3°C. The accuracy of the BRANZ Temperature Logger and the BRANZ Microvolt Logger was better than 0.2°C.

Chapter 4

Time Variation of Indoor Temperatures

Indoor temperatures are dynamic. Measuring the indoor temperatures at different times will result in different values for the indoor temperature. Analysis of time varying measurements can be aided by considering the different frequencies contributing to the measurement. Variations in the indoor temperature arise from variation due to (in approximate order of increasing frequency) changing climate, severity of the winter and summer seasons, weekly behaviours such as the difference between weekends and weekdays, the current weather (cold fronts passing thorough), daily day-night (diurnal) patterns as well as the heating patterns the occupants choose to use.

4.1 Climate Change

Climate change results in temperatures cycling from low values during ice ages, lasting about 100 000 years, to higher values during interglacial periods, lasting between 10–20 000 years (Taylor *et al* 1997). Climate change can also be much more rapid than this. The volcanic eruption of Mt. Pinatubo in the Philippines in 1991 ejected a large amount of ash and sulphur dioxide (SO_2) into the atmosphere and resulted in a drop of global temperature by about 0.5°C for approximately two years (Newhall, Hendley and Stauffer 1997).

It has been estimated that the global average surface temperature has increased by 0.6°C (IPCC 2001) over the 20th century. Furthermore, the Intergovernmental Panel on Climate Change (IPCC) reports (IPCC 2001) that most of the observed warming over the last fifty years is attributable to human activities, which have contributed to the increase in concentration in the atmosphere of Greenhouse Gases.

Greenhouse gases are a collection of gases, including carbon dioxide (CO_2), water vapour (H_2O) and methane (CH_4), that absorb longwave radiation such as the radiation emitted from the earth's surface which itself is heated by solar radiation. If no greenhouse gases were present in the atmosphere then the global average surface temperatures would have large fluctuations around a average temperature of -18°C rather than the relatively small fluctuations about 15°C that are presently experienced (Taylor *et al* 1997). Increasing the levels of greenhouse gases present in the atmosphere results in the 'Enhanced Greenhouse Effect' where more longwave radiation is absorbed in the atmosphere resulting higher global temperatures.

New Zealand produces around 0.5% of the world's greenhouse gas emissions (Ministry of Commerce 1999). Methane accounts for around 44% of New Zealand's greenhouse gas emissions, with carbon dioxide accounting for 39% and Nitrous Oxide (N_2O) another 16%. Methane and nitrous oxide are largely produced as a result of agricultural processes whereas carbon dioxide emissions (frequently from the burning of fossil fuels) comes from a greater range of sources such as domestic transport (15% of total emissions), industry (8%), electricity generation (7%), industrial processes (4%) and residential, commercial and agricultural (4%).

Global warming will have a follow through impact on the conditions within buildings. While warmer winters may result in reduced need for auxiliary space heating to increase the indoor temperatures to an acceptable level (Camilleri 2000), the increase in temperatures in summer may result in overheating in houses, which will require mitigation strategies (Jaques 2000).

4.2 Seasonal Patterns

The temperature within a building can vary throughout the year. The size of this temperature variation will depend on the severity of the local climate, the design of the building (for example, how much insulation, glazing and mass are present) and the total amount of heating and cooling used within the building. It is difficult enough to find any data on the indoor temperatures of buildings let alone the indoor temperatures of buildings over a number of years. Therefore the seasonal patterns will be examined from the average indoor temperatures in a sample of buildings rather than the indoor temperatures from individual buildings. This approach considers the overall impacts rather than the specific physical or social causes of the seasonal temperature variations.

It was seen in Section 2.2.3 that the lounge temperatures measured in the sample of 195 houses from the 1971-72 Electricity Survey were much colder during winter (an average temperature during August-September 1971 of 16.0°C) than during the following summer (an average February-March 1972 temperature of 20.5°C). While the 1971-72 study provided a good sample size it only contrasted temperature measurements at two times of the year.

Section 2.2.3 also reports on the study by Breuer on a smaller sample of 23 houses throughout New Zealand in which the monthly indoor temperatures were recorded over 1986 and 1987. These monthly temperatures are shown in Figure 4.1 along with the mean temperature for each month. The changes in temperature between the seasons are seen by the movement in the mean monthly temperature. The data from Breuer's study need to be treated with care due to the data collection and averaging methods used. The sample containing a high proportion of solar designed houses, a wide range of climates and the sample compostion frequently changed (houses dropping in and out of the sample).

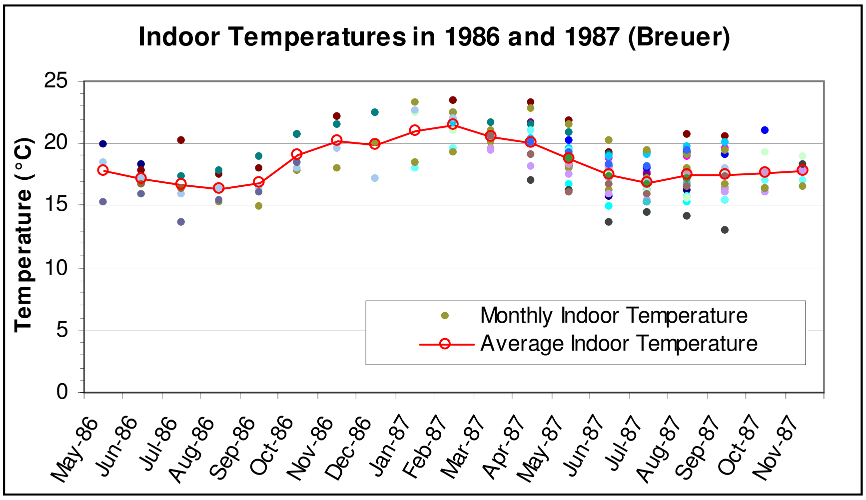


Figure 4.1 Indoor temperatures in Breuer' s sample of houses throughout New Zealand

During 1996 and 1997, HEEP (see Section 2.4.1) measured the indoor temperatures in 28 houses in Wanganui(see Table 2.3). The temperatures were recorded in a varying number of locations within each of the houses. As the number of sets of monitoring equipment was limited and the variation in indoor temperatures between houses unknown, it was decided to undertake measurements in four samples (‘rotations’ of the data logging equipment) of houses with each rotation (sample) taking place over half of the heating season (either leading up to, or away from, mid-winter).

The methods used to select the houses for each rotation differed. For the first two rotations in 1996 PowerCo - the electricity company in Wanganui, provided a number of ‘all-electric’ houses (initially only electricity use could be monitored with the data logging equipment) which included a number of staff houses. For the third rotation, the householders whose houses were supplied by two street transformers (about 100 houses in total) were approached to take part in the study (including some with solid fuel heaters) and for the fourth rotation, householders who had had an HERO (home energy rating options) energy audit (BRANZ 1993, Bassett, Amitrano and Mayson 1996) undertaken on their house were approached (again a number of households with solid fuel heaters were included).

The indoor temperatures in each of the houses were measured with a number of Tinytag temperature loggers (see Section 3.3.1) with measurements taken 15 minutes apart. A total of 2.4 million indoor temperature measurements were gathered from Wanganui. Because of the large amounts of data generated, data analysis requires the use of specialised computer software, use of global naming conventions and the development of sophisticated data processing routines.

An ‘import’ procedure has been developed, using Microsoft Excel, which merges all the ‘raw’ data (both temperature and energy) from the data loggers for each house allowing the data to be stored in a ‘pre-processed’ file, which can be imported into other programs, such as `S-PLUS`, when sophisticated analysis is required. The basis for data analysis is the pre-processed house file and when data is required over a number of houses, the relevant data summary from the pre-processed file for each house needs to be extracted or intermediate files containing selected data from each house need to be generated.

To generate a similar graph to Figure 4.1 the indoor temperatures from the 28 houses were assembled into a single file and a 1% random sample (twenty four thousand measurements) of this data selected. The 1% random sample was taken to allow analysis of the temperatures to be undertaken as the complete data were too large. Figure 4.2 shows a graph of this 1% sample which is similar in appearance to the original 2.4 Million data points and so will be taken as representative of the complete dataset. Figure 4.2 also shows a sinusoidal curve with a one-year period fitted to the data and a 14-day moving average of the hourly external temperature from Wanganui (NIWA Agent Number 3715) as recorded in the NIWA Climate Database (Penney 1997).

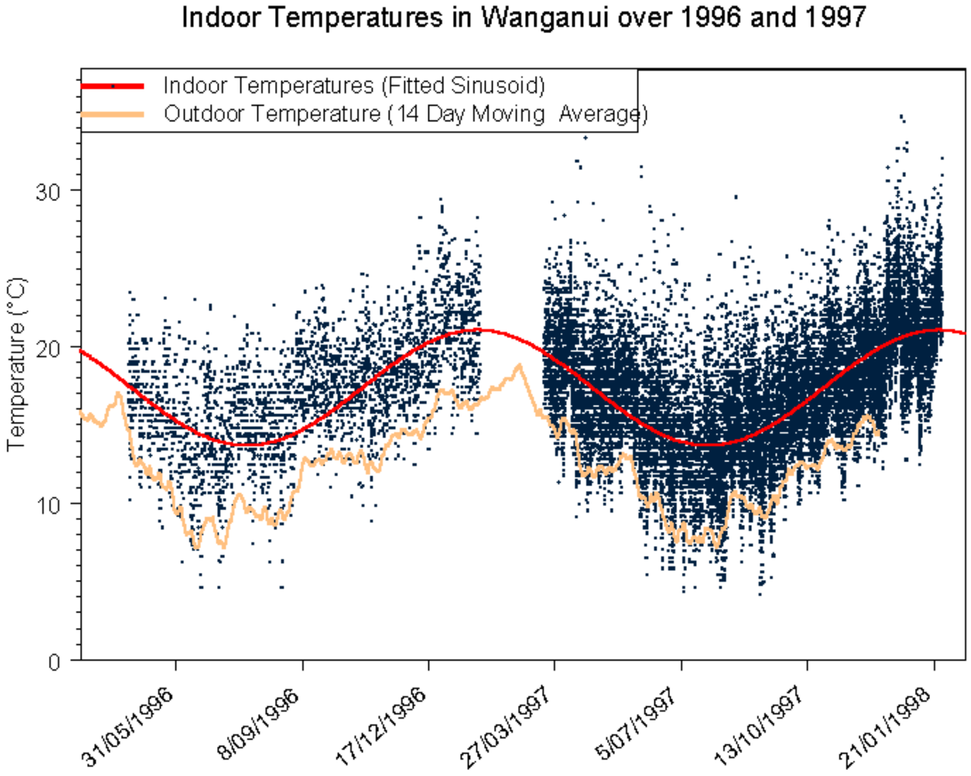


Figure 4.2 Indoor and outdoor temperatures from four sets of houses in Wanganui

The form of the fitted sinusoidal curve is

$$T = A\cos(\omega_0 t + \varphi) + T_0 \tag{4.1}$$

where for the sake of convenience, the time t, is measured in days so that the angular frequency ω_0 has a value of $\frac{2\pi}{365}$. The fitted parameters in equation (4.1) are A, T_0 and φ.

The fit of the sinusoid curve (4.1) to the 1% sample of indoor temperatures is reasonable and has a multiple-r^2 value of 42%. The fit shows that there are seasonal patterns in the indoor temperatures in the sample of buildings but that there are also other higher frequency processes taking place and these processes are important.

The fitting of the phase angle φ, can be taken as fixing the dates during the year when the maximum and minimum indoor temperatures occur. The fitted value of φ takes a value such that the minimum indoor temperature (13.7°C) occurs on the 26th July of each year. Fitting a sinusoid of the same form as equation (4.1) to the hourly external temperatures from the NIWA climate database also results in a minimum value for the 26th July. This ‘coldest day’ of the year for

Wanganui is about five weeks after the shortest day on the 21st June each year. Each year the dates of the expected maximum and minimum temperatures for a particular location can be expected to be the same and so the phase angle φ is taken as a constant for each location.

The other two fitted values; T_0 and A determine the mean yearly indoor temperature and the amplitude of the seasonal temperature swing respectively. The fitted values of T_0 and A are such that the minimum fitted temperature (on the 26th July) is 13.7°C and the maximum fitted temperature (on the 26th January) of 21.0°C. It is concerning that the minimum fitted value is quite low (below the 16°C risk threshold for respiratory infection, see Section 2.2.2) however the entire house is not occupied all of the time so this may not be the temperature level people are exposed to (Boardman 1991).

The two parameters T_0 and A, are more dynamic than φ and may slowly vary following climate change trends, yearly climate variations, changes to the overall quality of building and general changes in behaviour. When comparing the indoor temperatures of houses measured during different years (Pollard, Stoecklein and Bishop 1997), these variations are encountered and attributing the cause of any observed difference in the measured indoor temperatures is not straightforward. When comparing samples it is also important to consider the representativeness of the sample at each point in time to the assumed population it represents.

4.3 Higher Frequency Patterns

There are a number of factors that may give rise to higher frequency patterns in the indoor temperatures within a building. Some possible patterns may be;

- Weekly patterns due to people using the building in different ways on weekdays as compared with weekends.
- Weather patterns where passing warm or cold fronts influence the temperatures for a few days. It was seen from earlier work, that the indoor temperature recorded 24 hours previously was a strong influencer amongst a collection of environmental and time parameters (Pollard and Stoecklein 1998b).
- Diurnal (daily) patterns due to the daily cycle of solar radiation and outdoor temperatures.

- Heating patterns such as the time of day heaters are used. Frequently heaters are operated at specific times of the day such as in the evenings or the mornings. Section 4.8 of the HEEP Year 3 Report (Camilleri et al 1999) provides details of the time of day usage for a number of different types of heaters.

Patterns such as heating and differences in building use from weekends to weekdays may vary strongly from building to building so each building will be examined individually for higher order patterns.

As an example of the higher order patterns present in residential buildings, Figure 4.3 gives the magnitude of the Fourier transform of the indoor temperatures from each of the houses comprising the HEEP detailed temperature sample. The houses w11, w13, w16, w17, w18 were each monitored for between 120 and 124 days, whereas houses w19, w20, w26, w29 were monitored for a slightly longer time of between 187 and 190 days.

The Fourier transforms in Figure 4.3 show a clear diurnal pattern with a strong frequency component at 1 cycle per day. Additional frequency components are also seen at multiples of this frequency (2 and 3 cycles per day) indicating that the indoor temperatures have a characteristic daily pattern but that this pattern is not sinusoidal. It is difficult to establish the presence of lower frequency patterns in the Fourier transforms in Figure 4.3 as the transform becomes noisy and poorly defined. In particular weekly patterns (frequency around 0.14 cycles per week) are not distinct even when the x-axis range in Figure 4.3 is expanded.

The daily patterns identified in Figure 4.3 are due to both the response of the building to changes in the environment over the course of each day (daily cycles of solar radiation and outdoor temperature) and the use of heaters within the building at particular times of the day.

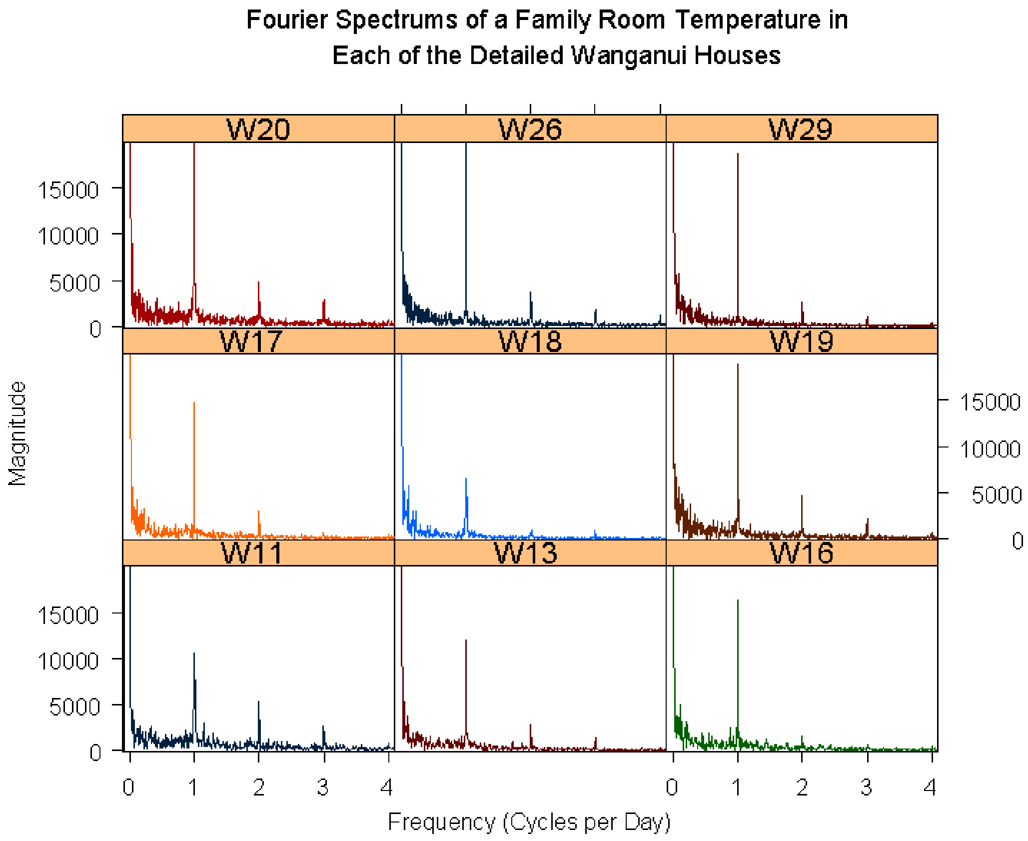


Figure 4.3 Fourier spectrums of the indoor temperatures in each of the HEEP detailed temperature sample houses.

A convenient way to examine daily temperature patterns is to compare the daily temperature patterns averaged over a number of days (temperature profile). The sample of days chosen for this averaging is a defining factor for the temperature profile.

Figure 4.4 shows monthly temperature profiles for the houses from the detailed temperature sample. The shapes of the summer temperature profiles are seen to be smooth and somewhat warmer that the winter temperature profiles. The winter temperature profiles are more uneven with sudden upturns in temperature presumably due to the use of heaters with the building. Pollard, Stoecklein and Bishop (1997) provides an example of this connection from a house in Wanganui where the time of upturns in the shape of the monthly temperature profiles are seen to be associated with periods of greater heater usage in the associated monthly heater profile. The upturns in the temperature profiles largely occur in the evenings from 6pm onwards when presumably the living room is occupied.

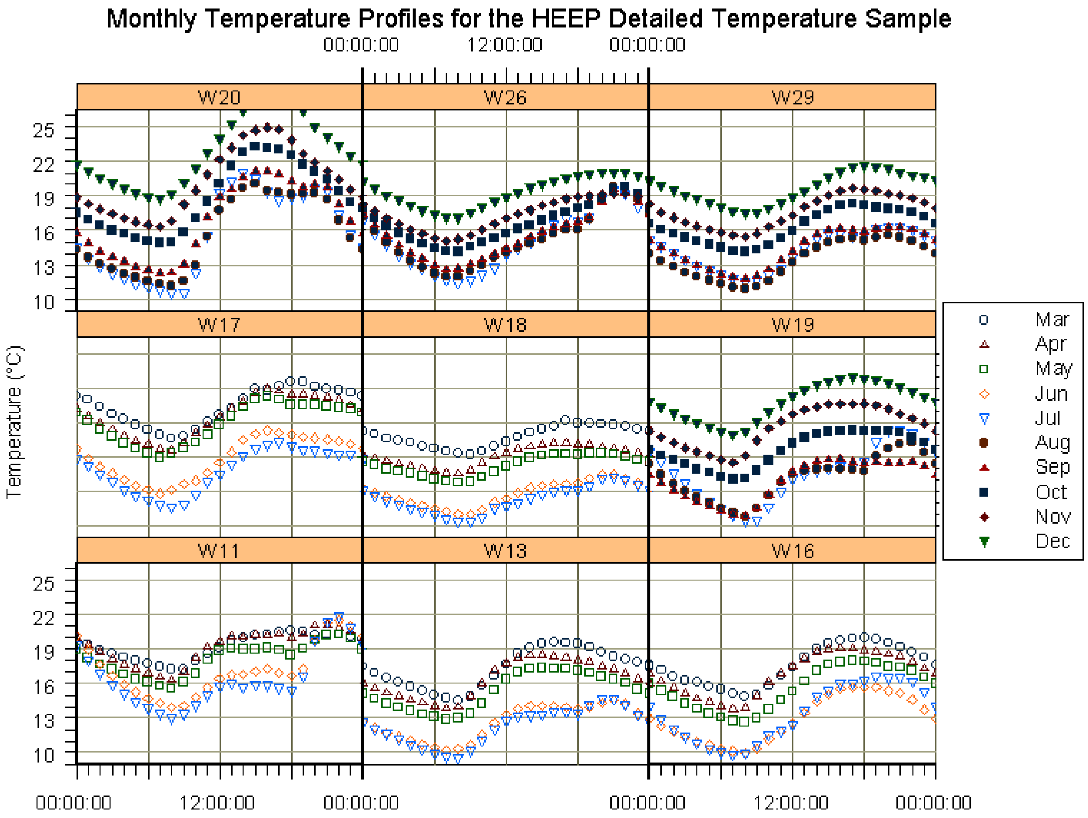


Figure 4.4 Average monthly temperature profiles from the detailed temperature sample

It is also interesting to see in Figure 4.4 that the variation over the day from house W20 is comparatively large. House W20 has a large area of window in the living room so the increase in temperature within the room due to solar gains is more rapid however the temperature also cools down more quickly (due to the lower thermal resistance value of single glazed windows as compared with the walls) so that the early morning temperatures within W20 are comparable to the other houses.

Houses are generally occupied on a daily basis. It may be expected that heating, if required, would also occur on a daily basis as well. Other types of buildings are not occupied on a daily basis, a church for example, where the building is predominantly used one day of the week (Sundays) with less usage during the remainder of the week. The indoor temperatures in All Saints Church, Palmerston North, were measured for this thesis and are examined in Chapter 6, however the time dependence of the temperatures within All Saints will now be briefly discussed.

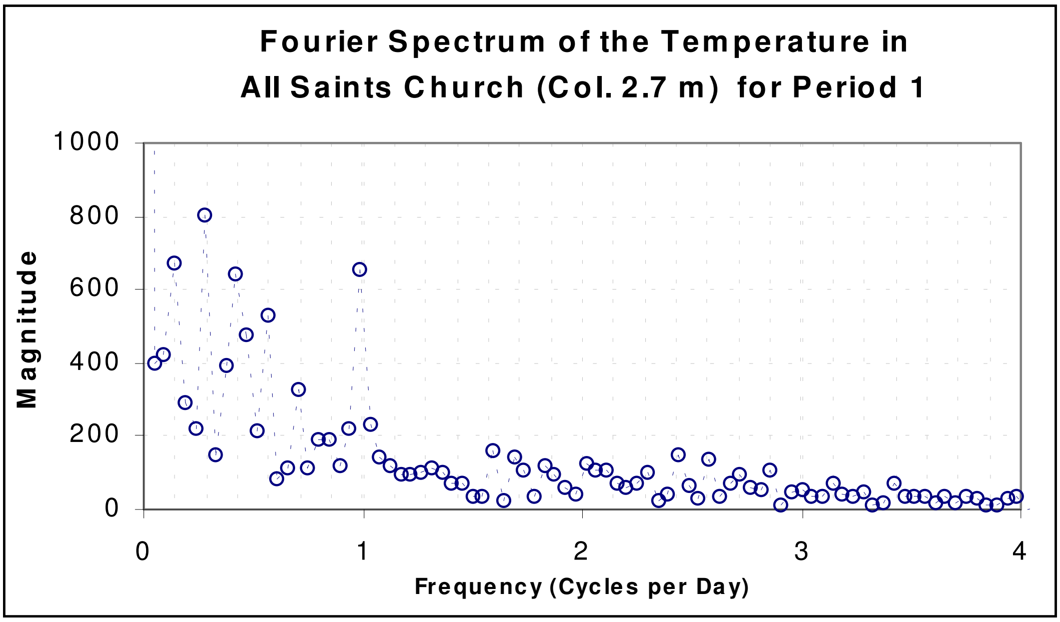


Figure 4.5 Fourier spectrum of the temperature in All Saints Church (Column 2.7 m) for Period 1

In order to examine the periodicity of the temperatures within All Saints, the first 2048 temperature measurements (taken 15 minutes apart) from the reference junction of the microvolt logger (mounted 2.7 m above the floor on the column) were Fourier transformed. A plot of the magnitude of the components of frequencies of less than 4 cycles per day is shown in Figure 4.5. Higher frequencies greater than 1 cycle per day do not contribute strongly to the temperatures patterns. A diurnal pattern (1 cycle per day) and lower frequency components (less than 1 cycle per day) are present in the Fourier spectrum. The first peak occurs at about 1 cycle per week with the other peaks occur at multiples of this value. As this block of data collection contained just over 3 weeks of data, the structure of the low frequency in the Fourier transform is not well defined, however the weekly pattern is clearly discernable. Future measurements on the temperatures could be done over a longer time interval to provide better estimates of the longer-term behaviour, which presumably is due to the differences in indoor temperatures in the church on Sundays.

4.4 Closure

The temperatures measured within a building will depend on when the measurements take place.

The indoor temperatures respond to the heating within a building. Heating generally only occurs in buildings for part of the day (or week) and a continuous average of temperature of an extended time will have a high weighting on periods when the building is unoccupied or unheated.

Temperature profiles provide indicative information on the heating occurring within the building.

In the next chapter, temperature variations due to the location of the measurement point within a single room of a residential building are examined.

Chapter 5

Room Temperatures Within a Residential Building

Temperatures within a building are not homogeneous. Temperatures will vary from room to room as well as varying within an individual room creating localised air temperature variations. In order to account for these localised temperature variations, models of the air temperature within rooms allow the room temperature at more than one point to be specified (van der Kooi and Förch 1985; Inard, Bouia and Dalicieux 1996). An extreme case of this is when mathematical models (CFD; Computational Fluid Dynamics) are used to calculate the room temperatures over a fine mesh covering the room volume (Saïd *et al* 1995, Chen and Jiang 1992). These methods have the limitation that only simple rooms (without detailing or furniture) and basic heating systems can be modelled.

This chapter will examine the variation in temperature within a single room by first examining data collected from a number of temperature loggers installed within the living room of a house in Palmerston North. Additional temperature measurements were also collected from a house in Whitby, Porirua, to allow specific comparisons to be made. Later in this chapter, ways of describing the observed temperature variations are examined.

5.1 Palmerston North House

The house chosen to examine in Palmerston North was in the suburb of Takaro. The house has a floor area of approximately 130 m^2 and was built in the early 1970's of a design that was frequently replicated at that time. The exterior of the house is shown in Figure 5.1.

Figure 5.1 Exterior of the Palmerston North house looking south

The construction of the house uses timber framing and includes a suspended timber floor, timber framed glazing and a pitched timber roof with a flat ceiling. The roofspace contains macerated paper insulation to an average depth of 100 mm. The roof cladding was corrugated steel. The living room is located centrally within the house with large windows in the northern wall. The ceiling of the room is at a height of 2.4 metres above the floor. A detailed floor plan for the house is shown in Figure 5.2 with Table 5.1 and Figure 5.3 indicating details of the positioning of the fourteen BRANZ Temperature loggers (identified with a T prefix) and four Tinytag Temperature loggers (identified with a TT prefix) used within the living room.

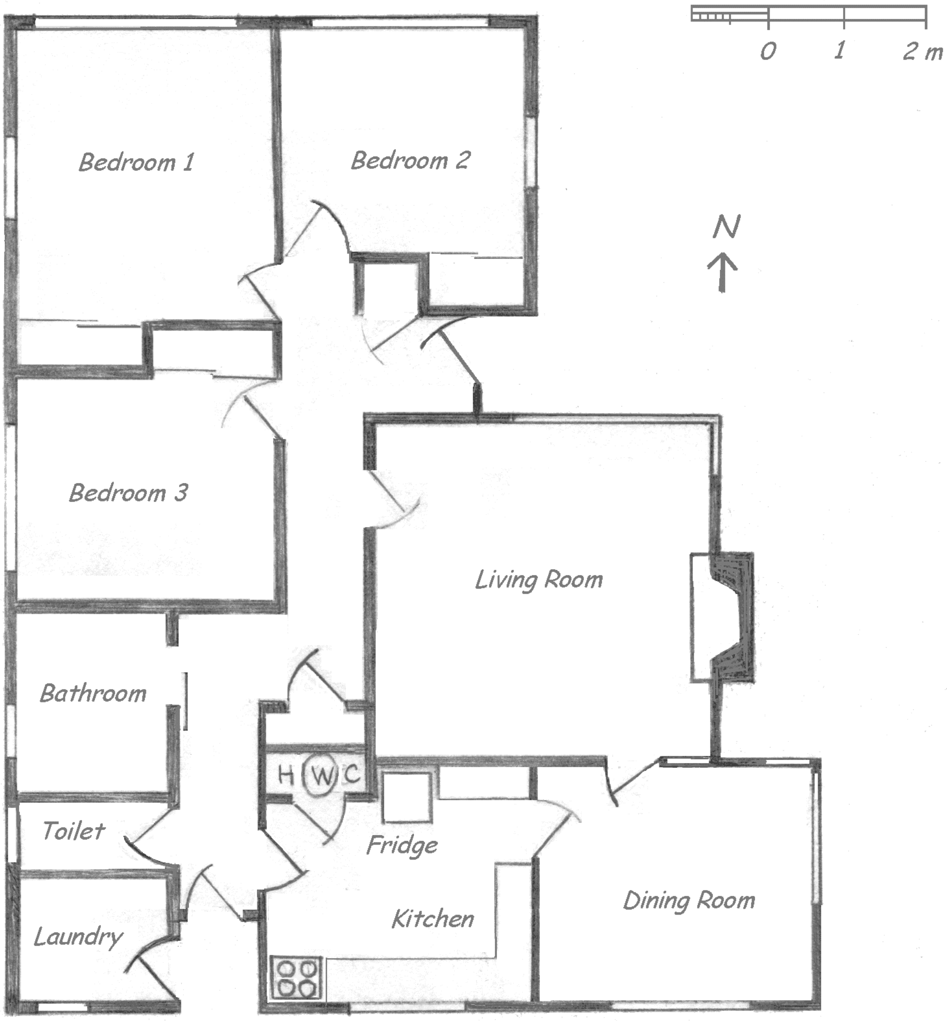


Figure 5.2 Floor plan of the Palmerston North house (scale 1:100)

Table 5.1 Selected positions for the temperature loggers

Sensor	**Height (m)**	**Description**
T14	1.9	Centre of room, suspended from light, shielded.
TT26954	1.9	Centre of room, on insulation on radiation shield (Tinytag)
T2	0.4	Array 1: 0.3 m in from S wall and W wall
T3	0.9	Array 1
T5	1.4	Array 1
T6	1.9	Array 1
T9	0.4	Array 2: 0.3 m in from N wall and W wall
T10	0.9	Array 2
T11	1.4	Array 2
T8	1.8	In wall unit S wall 1.4 m from W wall
T7	1.8	In wall unit S wall 2.3 m from W wall
T13	1.8	On shelf S wall 0.5 m from E wall
T16	2.0	Suspended from curtain rail E wall 1.0 m from N wall
T17	0.9	On Mantelpiece above gas fire 1.3 m from N wall
TT26964	0.5	On centre of gas heater 1.8 m from N wall (Tinytag)
T18	0.9	On Mantelpiece above gas fire 2.3 m from N wall
TT46101	1.9	Behind picture N wall 1.3 m from W wall (Tinytag)
TT26976	1.8	Behind picture W wall 1.7 m from S wall (Tinytag)

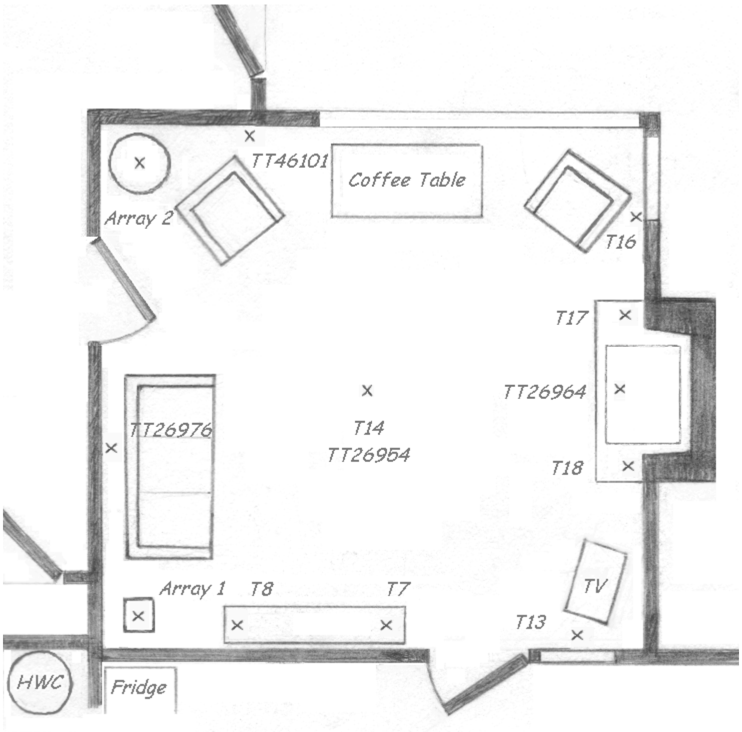


Figure 5.3 Arrangement of loggers within the living room

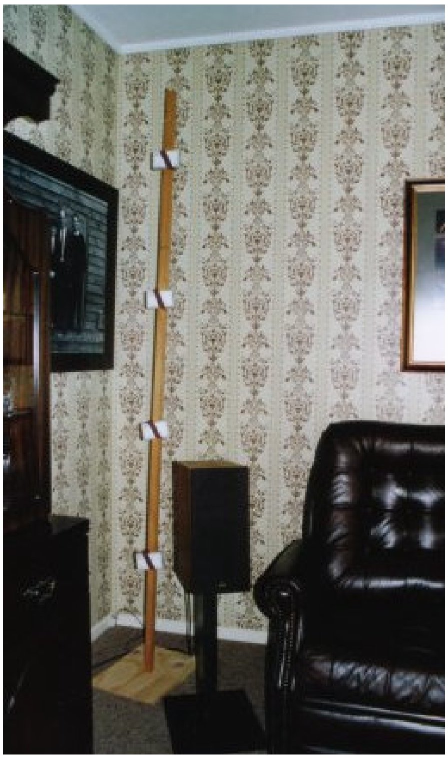


Figure 5.4 Temperature array 1 within the Palmerston North house

The placement of temperature loggers was intended to be comprehensive while not being too intrusive to the occupants. The most intrusive sensor was a BRANZ temperature logger covered by a radiation shield (constructed from a steel can), which was suspended from the light fixture in the centre of the room at a height of 1.9 m. The logger was separated from the radiation shield by a layer of 10 mm expanded polystyrene insulation. Details of the construction of the radiation shield are shown in Figure 5.5. A Tinytag temperature logger was placed on the top radiation shield (also isolated from of the radiation shield with a layer of 10 mm polystyrene) to provide data on the affects of shielding on the centre of room temperature measurement. Two vertical posts were used to place a series of BRANZ temperature loggers at a vertical separation of 0.5 m starting from a height of 0.4 m. These two arrays were placed in the west corners of the room. The southwest array contained four temperature loggers while the array in the northwest corner made use of an unused lamp stand, which restricted the array to three temperature loggers. The remaining six BRANZ Temperature Loggers were spread around the room. Two Tinytag's were placed behind pictures to see how this factor affects the reported temperature.

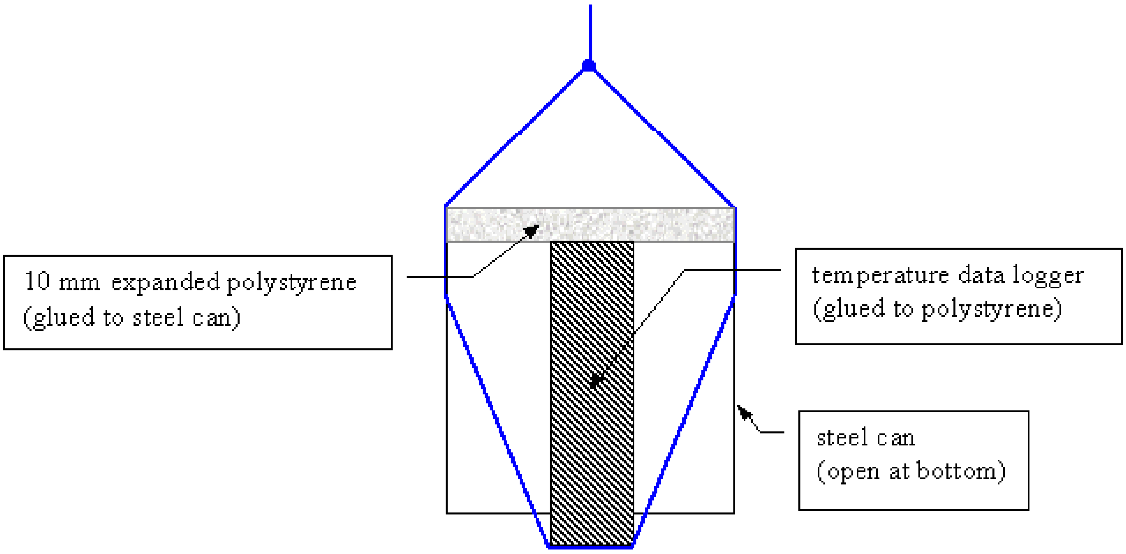


Figure 5.5 Construction of the radiation shield for the centre of room temperature logger

The temperature loggers were set with a five-minute interval between readings and measurements were made from the 20th May 1999 for a period of twenty-five days. Additional measurements, covering the same time period, of the external air temperature and global horizontal solar radiation were extracted from the NIWA climate database (Penney, 1997) using the hourly measurements taken from the Automatic Weather Station at Palmerston North Airport (NIWA Agent Number 3243). The global horizontal solar radiation is reported in the NIWA database as the solar radiation received (in MJ· m^{-2}) by a horizontal collector for the previous hour. This measurement site is approximately four kilometres to the northeast of the house being measured so there may be some variation due to localised conditions.

The sole active heating used within the living room over the monitoring period was a flued reticulated natural gas radiant heater located on the eastern wall. A Tinytag temperature logger placed on top of the gas heater was used to provide an indication of when the heater was being used. Figure 5.6 shows the gas heater and the Tinytag temperature logger positioned on it.

Figure 5.6 Reticulated gas heater

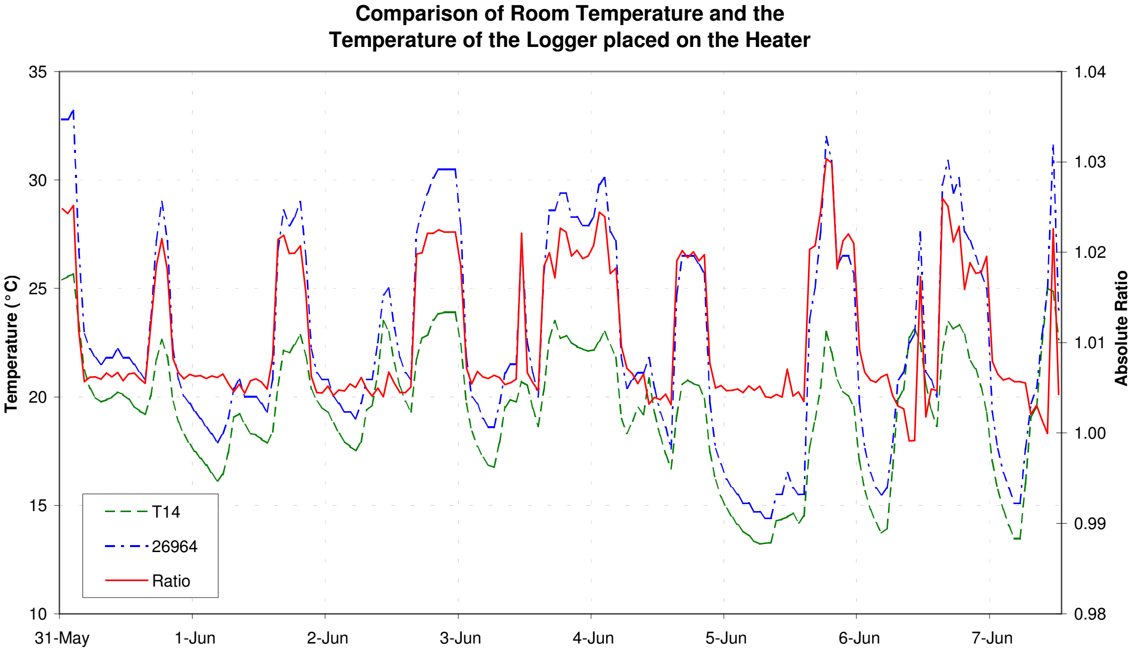


Figure 5.7 The centre of room temperature, the temperature of the logger on top of the heater and the ratio of their absolute temperatures

The ratio of the absolute temperature reported by the logger positioned on the heater to the absolute temperature at the centre of the room shows clear transitions as can be seen in a time series of the ratio given in Figure 5.7. A value of the ratio of 1.01 seems to distinguish between background noise and physically meaningful events in the logger data. It was expected that these events would solely be the operation of the heater. An average time of day profile for the temperature logger outputs for the centre of room logger, the logger placed on the heater and the two loggers placed on the mantelpiece are shown in Figure 5.8, where localised peaks (around 15:00) are seen in the temperatures reported by the logger on the heater and the loggers on the mantelpiece.

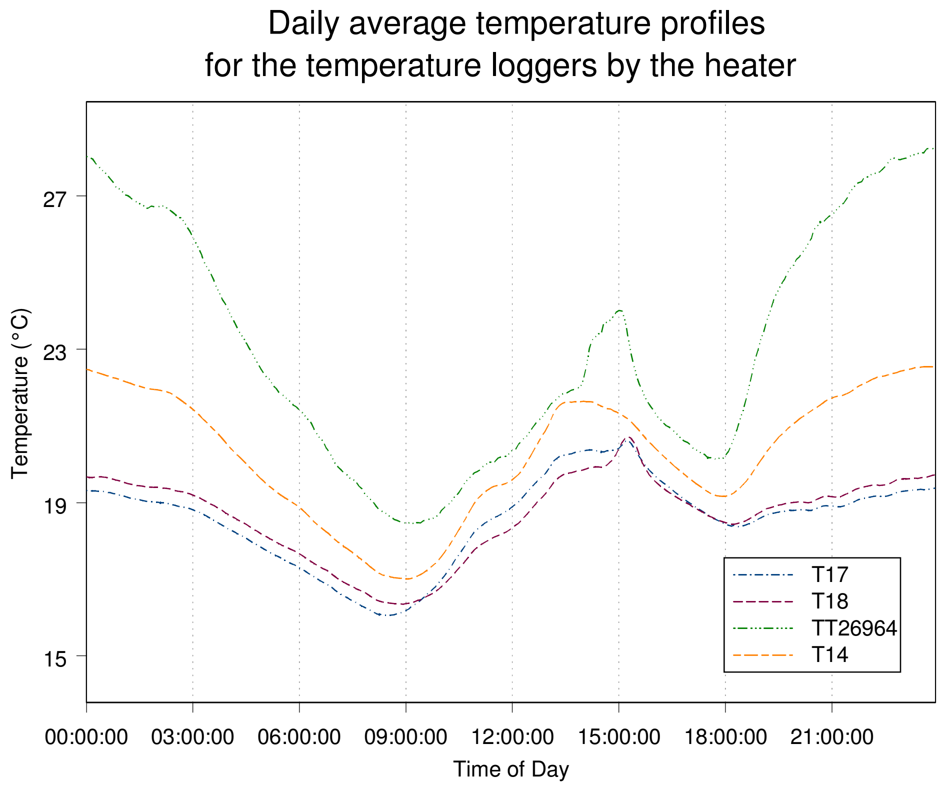


Figure 5.8 Temperature profiles of loggers by the heater

The occupant indicated that heating was only used in the evening. The loggers on the heater were in the direct solar path at 15:00 so these spikes in the temperatures were due to the direct solar radiation heating the logger rather than the operation of the heater. The hourly estimates of the heater being on or off were adjusted so that they had a value of zero at 15:00.

5.2 Temperature Patterns Within the Room

Time-series graphs of the indoor temperatures provide a considerable opportunity for descriptive and qualitative analysis. Figure 5.9 shows the readings from the temperature loggers over a

4½ day period. The tick mark indicates the 00:00 (midnight) reading at the start of the day indicated by the label. The high reading record (TT26964) is from the temperature logger positioned on the gas heater. The extended high values occur in the evening when the heater is in operation. The short spikes occurring in the afternoon's are due to solar radiation warming the room. The narrow spike on Thursday 3rd June occurs at 15:00 and is due to direct solar radiation striking the logger placed on the heater. The heating on Thursday evening initially raises the room temperatures but then seems to be turned down, a recharge then boosts the room temperatures again early in the morning on Friday. The temperatures remain low during Friday and drop overnight to around 15°C.

The temperatures appear to have a greater range (4–5°C) while the heater is being used rather than the 2–3°C range occurring in the morning once the room has cooled down. The temperature sensor T8 appears to have a relatively slower decay that the other temperature sensors.

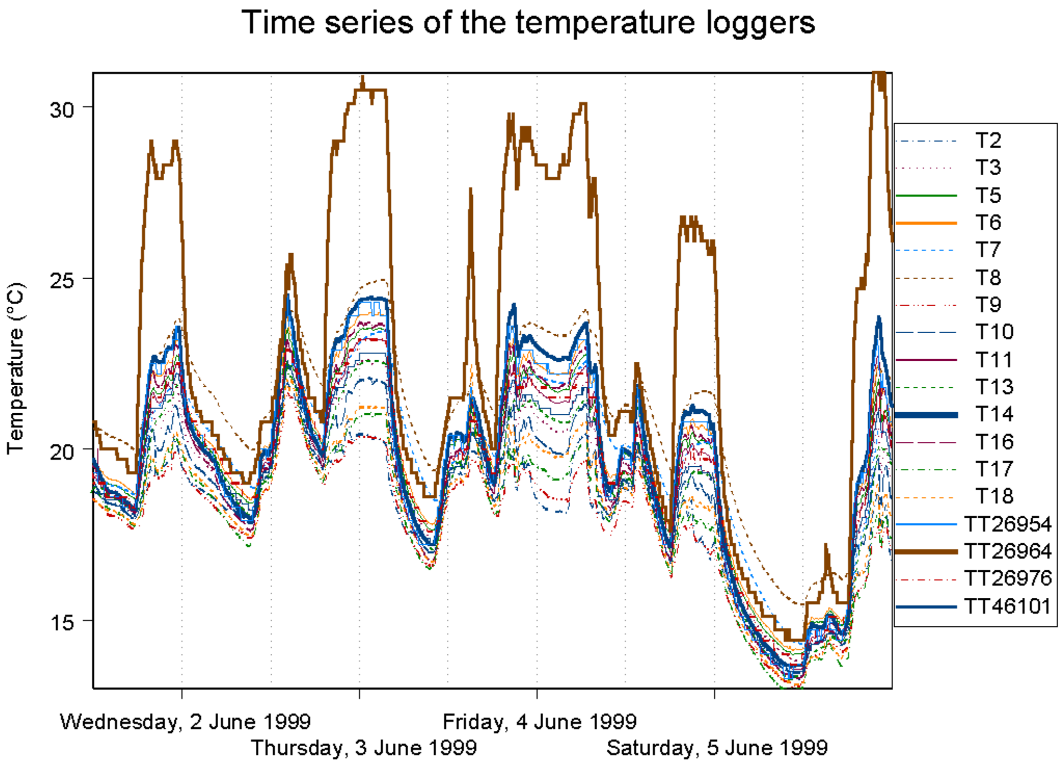


Figure 5.9 Time series of all the temperatures over a 4 ½ day period

A more systematic analysis of the temperature profiles requires a more quantitative approach. Table 5.2 gives some basic statistical properties of the values reported for each logger for the twenty five days.

Table 5.2 Summary properties of the all of the room temperature loggers (excludes logger on heater)

	T2	**T3**	**T5**	**T6**	**T7**	**T8**
Minimum:	12.69	13.15	13.32	13.40	14.27	15.25
1st Quartile:	17.09	18.17	18.57	18.84	18.93	20.14
Mean:	18.37	19.42	19.96	20.24	20.17	21.45
Median:	18.64	19.77	20.22	20.47	20.45	21.73
3rd Quartile:	19.77	20.79	21.54	21.97	21.62	22.98
Maximum:	23.20	24.98	25.53	25.98	24.97	26.65
Missing Values:	0	0	0	0	0	0
Variance:	3.98	5.07	6.07	6.56	4.81	5.44
Standard Deviation:	1.99	2.25	2.46	2.56	2.19	2.33
Skewness:	.43	.43	.39	.37	.47	.43

	T9	**T10**	**T11**	**T13**	**T14**	**T16**
Minimum:	12.37	12.72	12.87	12.61	12.85	12.08
1st Quartile:	16.94	17.74	18.18	18.04	18.53	18.24
Mean:	18.13	18.95	19.61	19.31	20.26	19.80
Median:	18.46	19.31	19.91	19.69	20.37	20.05
3rd Quartile:	19.43	20.27	21.19	20.92	22.33	21.75
Maximum:	23.27	24.56	25.38	24.87	27.16	26.55
Missing Values:	0	0	0	0	0	0
Variance:	4.02	4.96	6.30	5.86	8.47	7.96
Standard Deviation:	2.00	2.23	2.51	2.42	2.91	2.82
Skewness:	.52	.44	.37	.52	.25	.38

	T17	**T18**	**TT26954**	**TT26976**	**TT46101**	**Pooled**
Minimum:	11.76	12.44	12.60	13.30	13.50	11.76
1st Quartile:	17.17	17.49	18.30	18.53	18.50	18.04
Mean:	18.56	18.66	20.05	19.74	19.65	19.55
Median:	18.93	18.99	20.00	20.00	20.10	19.73
3rd Quartile:	20.06	20.00	22.20	21.50	21.20	21.12
Maximum:	26.80	26.86	27.20	24.70	24.80	27.20
Missing Values:	0	0	0	0	1419	1419
Variance:	5.54	4.87	8.42	5.83	5.54	6.53
Standard Deviation:	2.35	2.21	2.90	2.42	2.35	2.56
Skewness:	.36	.42	.29	.44	.52	.23

All the temperatures exhibit positive skewness. Heating will have the effect of raising the temperatures however as the heating is operated in an ‘on-demand’ mode, heating will not always be applied and the low temperature tail of the distribution will remain. Figure 5.10 shows density plot functions of the temperature values for the centre of room logger and the loggers making up the array in the southwest corner of the room. These density plots have been created using `S-PLUS` using a Gaussian filter.

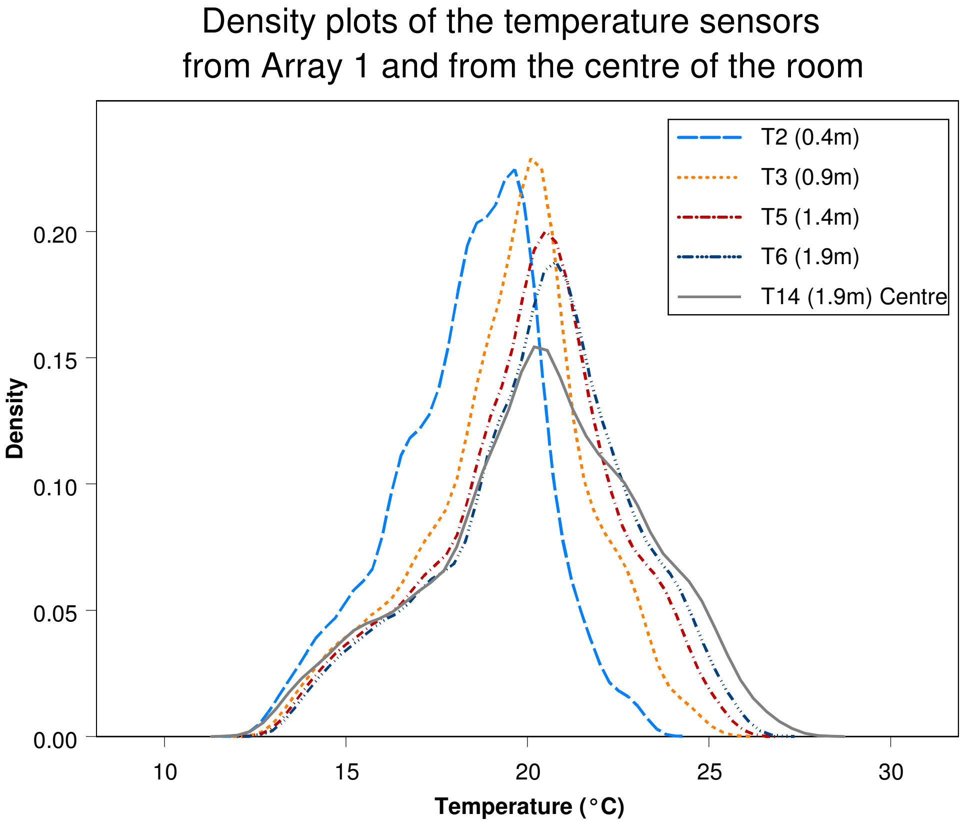


Figure 5.10 Density plots (Gaussian filtered) of the temperatures from array 1 and the centre of room temperature

The box plot is a convenient graphical display of the range of a variable and shows the maximum, upper quartile, median, lower quartile and minimum values for the data. Figure 5.11 shows box plots for the temperature loggers used within the room (other than the logger placed on the gas heater). From the box plots it can be seen than the range for each location is large but is roughly comparable between logger locations. It can also be seen that there is a distinction in the median level between the loggers. This distinction appears to be associated with the height of the logger. The loggers placed at a low height (T2, T9) appear to have a lower range of operation while those loggers placed at a higher height have a higher range of operation.

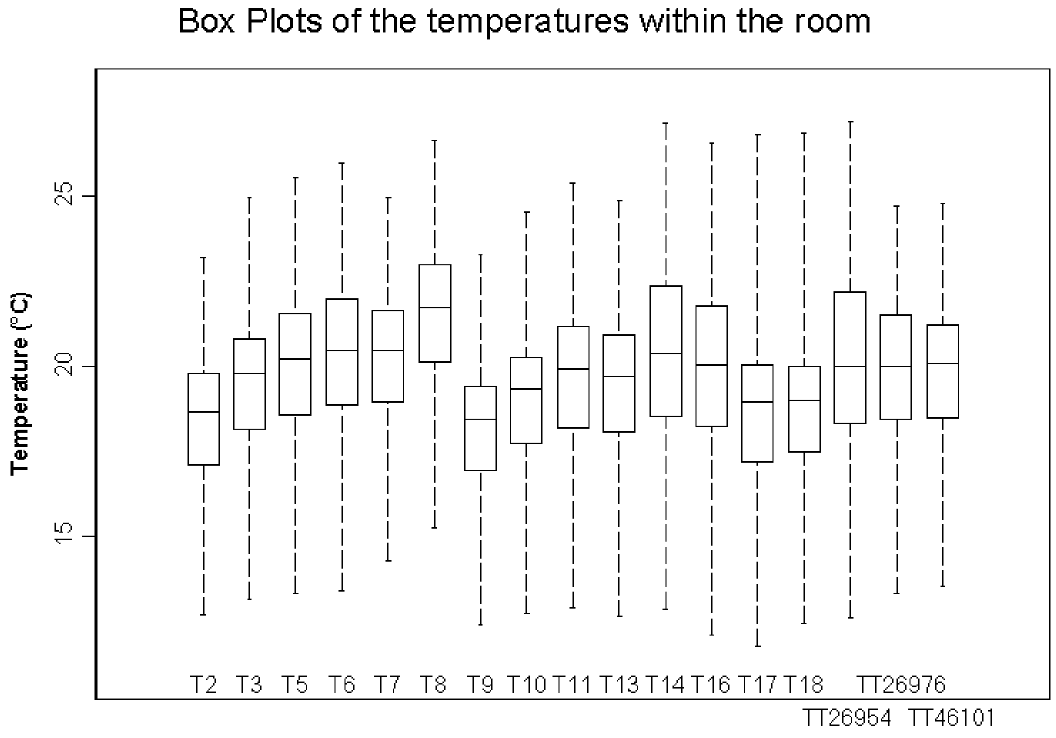


Figure 5.11 Box plots of all the room temperatures

While the box plots of Figure 5.11 and the summary statistics of Table 5.2 indicate that the measures of spread of the temperatures are similar, the inter-relationship between the temperature records as well as their time-dependent behaviour is not contained within this data. The inter-relationship between two temperature loggers can be examined by plotting a scatter-plot of the temperatures reported at the same time from each logger with the readings from one logger put on the x-axis and the readings from the other logger placed on the y-axis. Each pair of temperature measurements requires a separate scatter-plot.

Figure 5.12 shows this 'matrix-pair scatter-plot' for the temperature loggers making up the southwest array as well as the temperature logger measuring the centre-of-room temperature. From Figure 5.12 it can be seen that all the temperatures are reasonably correlated with one another and that the nature of this correlation is approximately linear. The bulging is the greatest when comparing low positioned temperature loggers to high positioned temperature loggers.

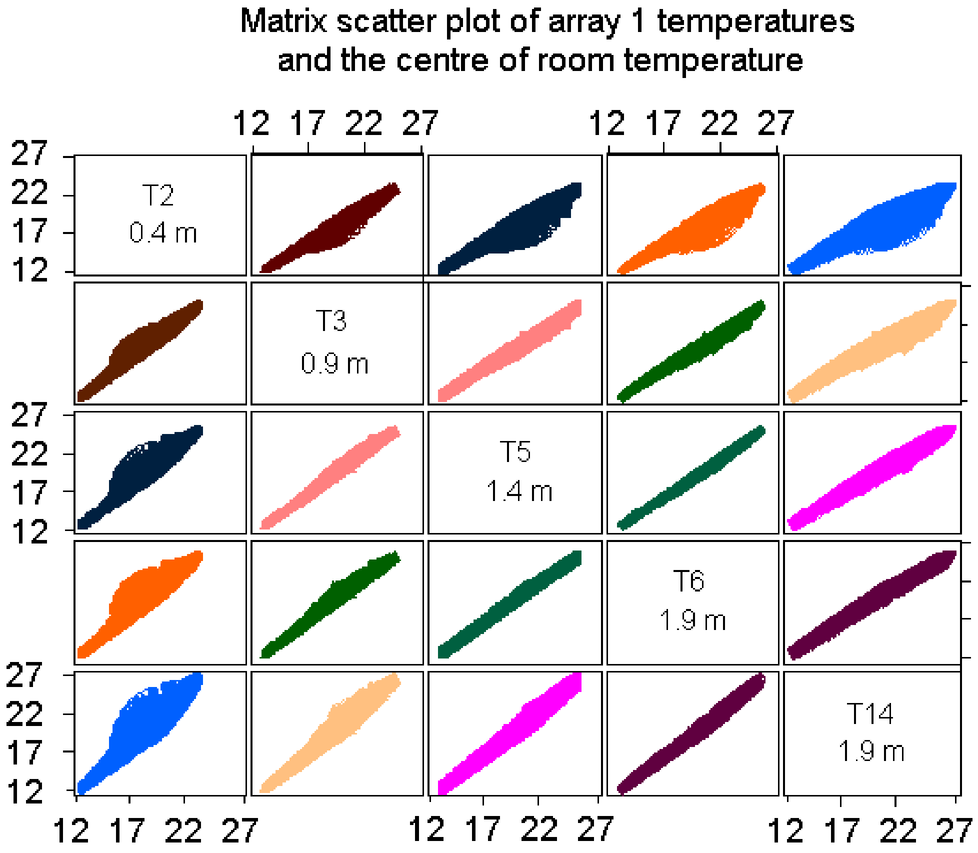


Figure 5.12 Matrix pair scatter-plot of the temperatures from array 1 and the centre of room temperature

As the inter-relationship between instantaneous temperature measurements appears linear, the Pearson's Correlation Coefficient can be used to give the degree of linear association between the temperatures. Table 5.3 gives the Correlation Coefficient for each possible pair of temperature loggers arranged by the height of the temperature logger. Darker grey shading in this table indicates a lower degree of correlation. The bulging observed in the matrix-pair scatter-plot will be reproduced as a lower Correlation Coefficient.

The height of the temperature logger appears to be an important variable in determining the temperature from the logger. It was decided to gather temperature-height information from another house so that the contributing factors to the vertical temperature distribution could be explored. The second house was located in Whitby and details of this monitoring are given in the next section before a more detailed examination of the vertical temperature distribution is undertaken.

Logger		T9	T2	T3	T10	T18	T17	T5	T11	TT26976	T13	T8	T7	T6	T14	TT46101	TT26954	T16	
	Height	0.40	0.40	0.90	0.90	0.90	0.90	1.40	1.40	1.80	1.80	1.80	1.80	1.90	1.90	1.90	1.90	2.00	
T9	0.40	1.000	.989	.979	.984	.985	.984	.954	.953	.953	.965	.936	.917	.944	.913	.931	.919	.936	T9
T2	0.40	.989	1.000	.965	.968	.968	.965	.934	.932	.932	.942	.914	.897	.923	.888	.906	.896	.909	T2
T3	0.90	.979	.965	1.000	.998	.987	.968	.994	.992	.985	.981	.970	.945	.989	.972	.958	.970	.977	T3
T10	0.90	.984	.968	.998	1.000	.989	.975	.989	.989	.981	.979	.963	.937	.983	.965	.955	.965	.976	T10
T18	0.90	.985	.968	.987	.989	1.000	.983	.974	.972	.971	.978	.959	.938	.967	.944	.946	.943	.960	T18
T17	0.90	.984	.965	.968	.975	.983	1.000	.946	.944	.936	.949	.914	.889	.937	.916	.922	.928	.947	T17
T5	1.40	.954	.934	.994	.989	.974	.946	1.000	.999	.992	.980	.977	.950	.999	.990	.965	.982	.986	T5
T11	1.40	.953	.932	.992	.989	.972	.944	.999	1.000	.991	.978	.974	.946	.998	.990	.965	.982	.988	T11
TT26976	1.80	.953	.932	.985	.981	.971	.936	.992	.991	1.000	.992	.989	.971	.991	.975	.967	.961	.971	TT26976
T13	1.80	.965	.942	.981	.979	.978	.949	.980	.978	.992	1.000	.990	.977	.977	.952	.961	.937	.956	T13
T8	1.80	.936	.914	.970	.963	.959	.914	.977	.974	.989	.990	1.000	.993	.975	.952	.955	.928	.945	T8
T7	1.80	.917	.897	.945	.937	.938	.889	.950	.946	.971	.977	.993	1.000	.948	.916	.937	.888	.908	T7
T6	1.90	.944	.923	.989	.983	.967	.937	.999	.998	.991	.977	.975	.948	1.000	.994	.966	.985	.987	T6
T14	1.90	.913	.888	.972	.965	.944	.916	.990	.990	.975	.952	.952	.916	.994	1.000	.955	.992	.988	T14
TT46101	1.90	.931	.906	.958	.955	.946	.922	.965	.965	.967	.961	.955	.937	.966	.955	1.000	.948	.949	TT46101
TT26954	1.90	.919	.896	.970	.965	.943	.928	.982	.982	.961	.937	.928	.888	.985	.992	.948	1.000	.986	TT26954
T16	2.00	.936	.909	.977	.976	.960	.947	.986	.988	.971	.956	.945	.908	.987	.988	.949	.986	1.000	T16

Table 5.3 Correlation matrix of the temperature measurements

5.3 Whitby House

This second example building (shown in Figure 5.13) is located in Whitby, a suburb of Porirua. This house is a smaller (90 m^2) and more open plan than the house measured in Palmerston North. As the house was built in 1985, the construction of the house includes insulation levels as per NZS4218P:1977. The construction of the Whitby house includes a suspected timber floor incorporating drapped foil as underfloor insulation. The roofing is corrugated galvanised iron with R2.2 (100 mm) fiberglass batts used as insulation in the roofspace. The exterior wall construction is timber framing and is clad with Hardiplank cladding. The exterior walls are insulated with the use of foil-backed 9.5 mm plasterboard (Gibfoil) on the interior side of the framing.

Figure 5.13 View of Whitby house looking northeast

A floor plan for the Whitby house is shown in Figure 5.14. The temperature array was positioned in the northwest corner of the living room (shown in Figure 5.15) and temperature measurements were collected at five-minute intervals over two periods, one twenty five day period during summer (5th February 2000 to 29th February 2000) and one nineteen day period during winter (8th June to 26th June 2000). The winter period was shorter due to a logger failure.

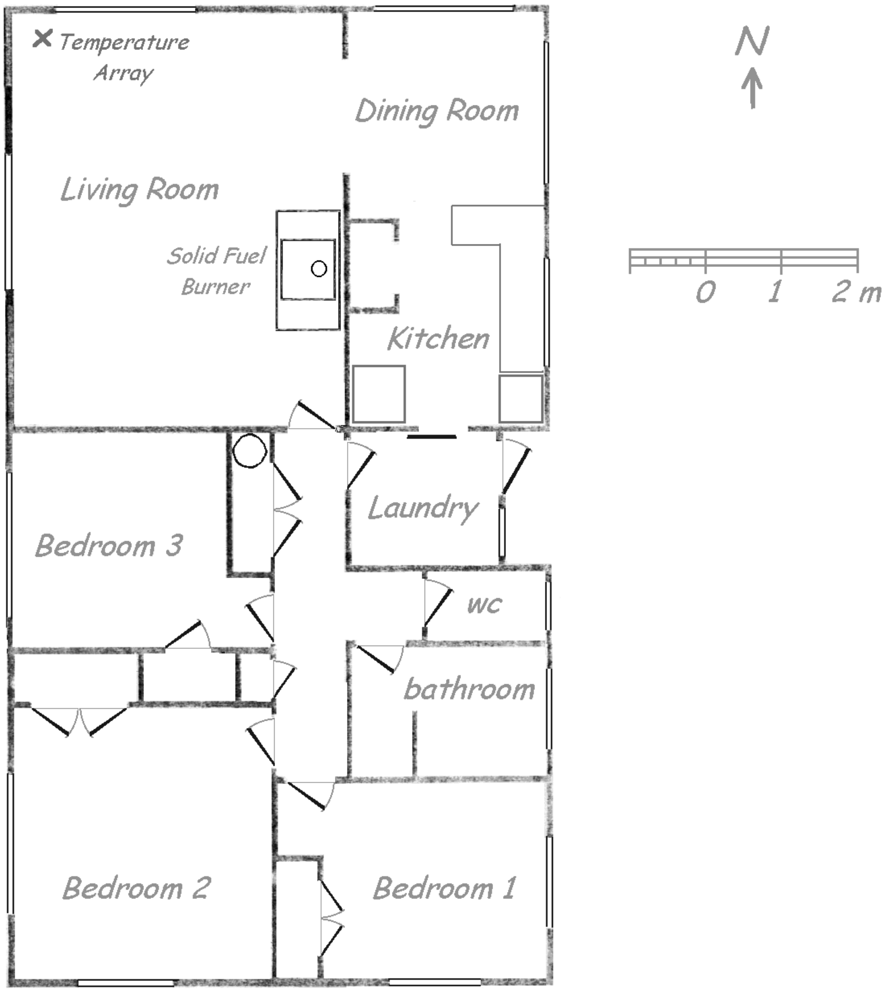


Figure 5.14 Floor plan of the Whitby house (scale 1:100)

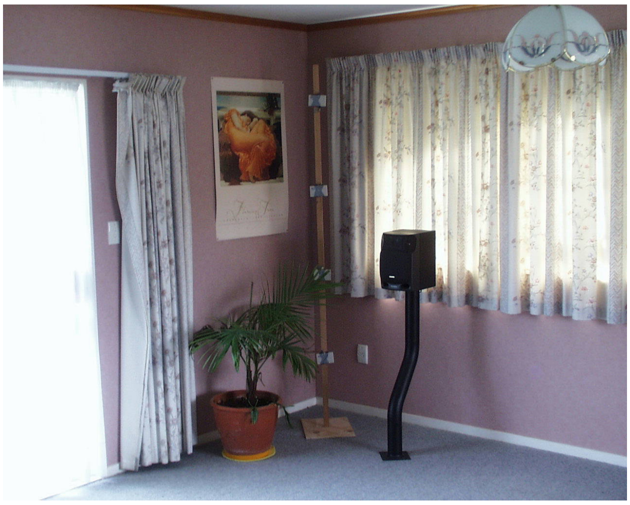


Figure 5.15 Whitby temperature array

The heating used within the living area of the house was a free-standing woodburner (shown in Figure 5.16). A tinytag temperature logger was modified by replacing the thermistor with a high temperature thermistor which was attached to the external top left surface of the firebox of the woodburner.

Figure 5.16 Solid fuel heater used in the Whitby house

The sole occupant of the Whitby house did not use the woodburner during the summer monitoring period and only used it infrequently during the winter period. The summary statistics of the temperature logger measurements for summer and winter are given in Table 5.4. The temperatures in the Whitby house during winter are much lower than the temperature in the Palmerston North house, which was also measured over winter.

Table 5.4 Summary statistics from the Whitby temperature array during summer and winter (over page)

SUMMER

	T06	**T100**	**T12**	**T11**	**Pooled**
Minimum:	13.73	14.25	14.22	14.00	13.73
1st Quartile:	19.30	19.77	19.87	19.77	19.64
Mean:	20.42	21.06	21.23	21.18	20.97
Median:	20.45	21.08	21.23	21.13	20.94
3rd Quartile:	21.74	22.48	22.75	22.72	22.43
Maximum:	25.21	26.26	26.55	27.07	27.07
Variance:	3.95	4.49	4.90	5.21	4.74
Standard Deviation:	1.99	2.12	2.21	2.28	2.17
Skewness:	.29	.20	.16	.10	.14

WINTER

	T100	T101	T102	T103	Pooled
Minimum:	6.11	6.27	6.50	6.53	6.11
1st Quartile:	11.63	11.80	12.04	12.09	11.90
Mean:	12.78	13.00	13.30	13.51	13.15
Median:	13.08	13.27	13.52	13.59	13.34
3rd Quartile:	14.34	14.59	14.80	14.93	14.65
Maximum:	19.33	19.97	21.53	25.73	25.73
Variance:	4.81	5.12	5.76	7.28	5.81
Standard Deviation:	2.19	2.26	2.40	2.70	2.41
Skewness:	.57	.48	.18	.49	.03

5.4 Vertical Temperature Distribution

It was seen in section 5.2 that the height of the temperature logger was identified as distinguishable factor of the temperature profiles from the Palmerston North house. The temperature of the air within a room will vary due to the internal air movement. As air is heated its density will reduce becoming more buoyant and will rise within the room. The interaction of warmed air and the other air within a room is not easily determined. The manner in which the air is heating (Howarth 1985; Pollard, O'Driscoll and Pinder 2001) and the locations of heaters (Inard, Bouia and Dalicieux 1996) are important factors.

Information on the vertical temperature distribution was examined for the Palmerston North house by using data from the two vertical arrays within the room. The twenty-five days of records provided 7200 instantaneous temperature - height profiles. Figure 5.17 shows eight temperature-height profiles from array 1 (southwest corner) taken three hours apart on Wednesday 2nd June 1999. Array 1 consists of four temperature loggers placed at heights of 0.4 m, 0.9 m, 1.4 m and 1.9 m. It should be noted that the smoothed lines shown in Figure 5.17 that connect the data points do not represent measurements or a functional relationship but are used to identify measurements taken at the same time. As the height of the measurement is increased, the temperatures reported by the loggers monotonically increase but with a reducing magnitude.

The first temperature-height profile is for 00:00 (midnight) after heating has been applied the previous night resulting in the profile having a high level. The first profile also has quite steep curvature. The next three profiles show a dropping temperature level with a greater reduction in temperatures from the loggers at a higher height reducing the steepness of the profile. The mid-day profile shows a recovery in the level of the profile however the steepness of the profile does not seem to increase. The 15:00 profile is the highest profile. The 15:00 profile also exhibits a greater curvature but not as extreme as the 00:00 profile. The temperature level and degree of curvature for the 18:00 profile is approximately mid-way between the 15:00 profile and the 9:00 profile. Finally, while heating is being applied, the 21:00 profile is similar to that observed at mid-night but of a slightly higher level but with a similar steep curvature.

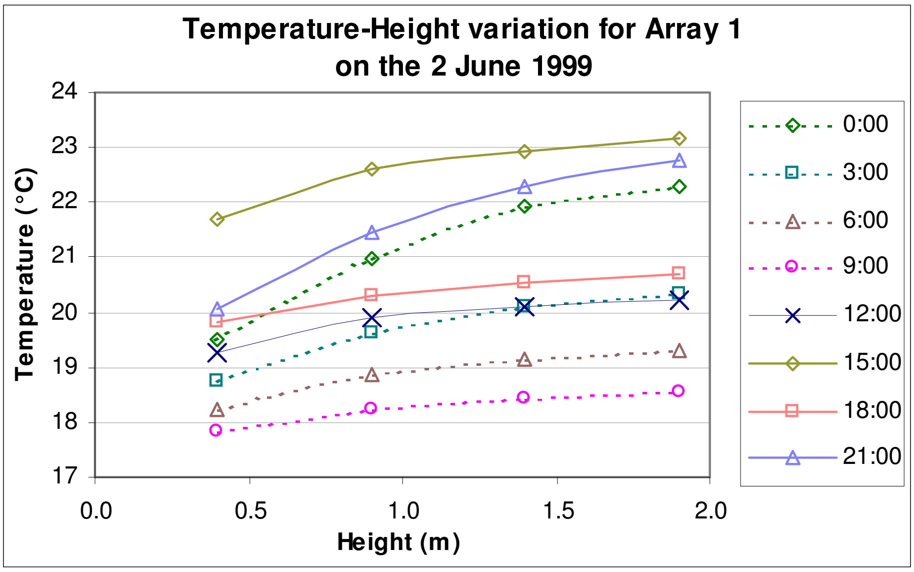
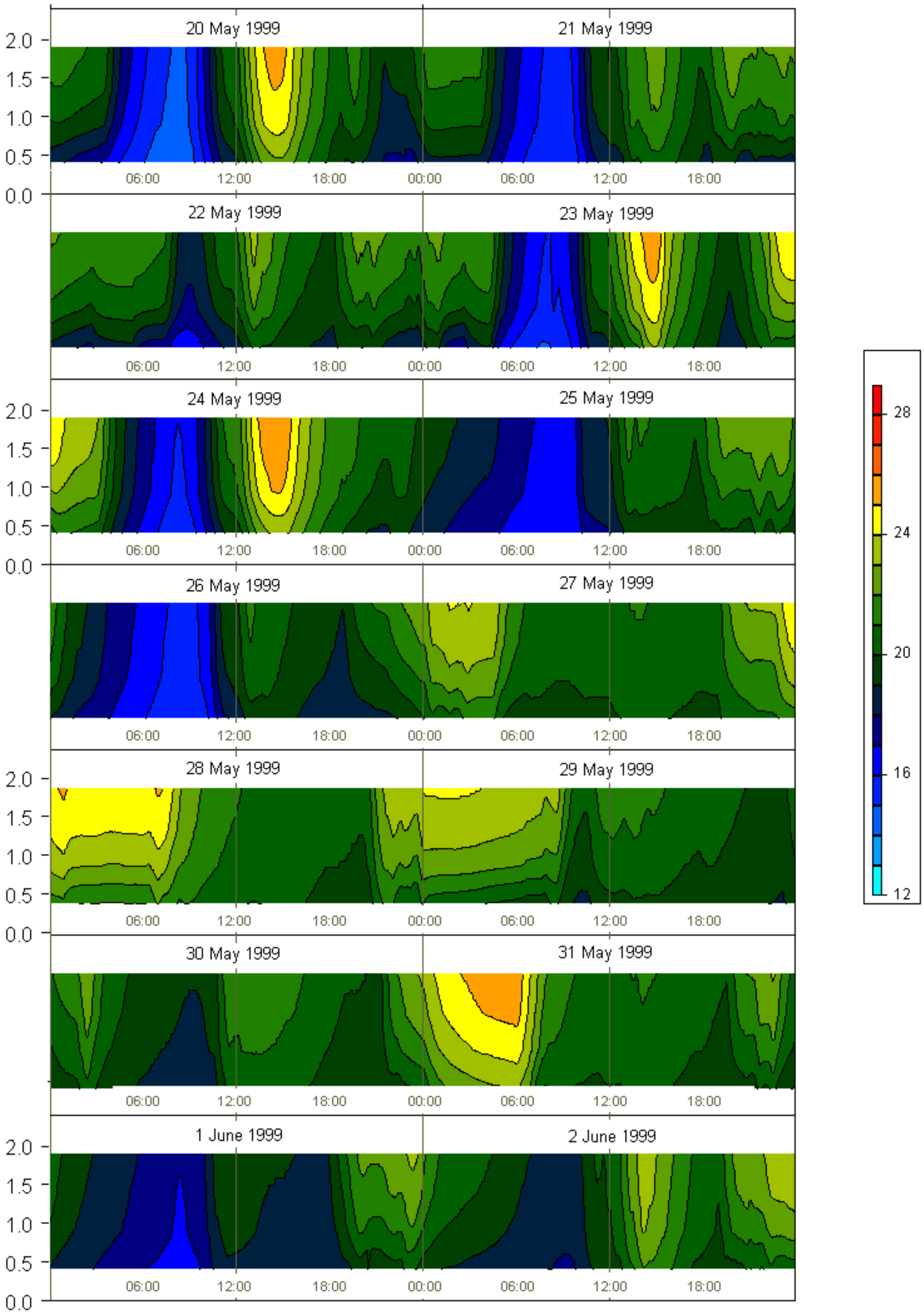


Figure 5.17 Temperature – height relationship for array 1 (Palmerston North, southwest corner)

The temperature-height graph of Figure 5.17 has a limitation that only a few profiles can be displayed without cluttering the graph and making the time dependence of the profiles difficult to examine. Figure 5.18 shows a different representation of the temperature-height data. Time is displayed on the x-coordinate axis with the height shown on the y-coordinate axis. Colour is used to indicate the temperature at each discrete combination of time and height. The density of the measures is much higher for the time axis, with 288 measurements each day, than for the height axis, which only has four measurements. The graphing program (`S-PLUS`) is then left to create a continuous surface of colour from the discrete measurements. The time axis has been broken up to display two days from each 'strip' of the graph. The 2nd of June is repeated as the graph is continued over the page.

The level of a profile in a temperature-height graph (Figure 5.17) corresponds to a colour in the temperature-height-time graph (Figure 5.18). The curvature of a profile in a temperature-height graph profile corresponds with the spacing of the vertical contours in the temperature-height-time graph. The temperature-height-time graph also provides additional information of the rate of temperature change at a particular height through the spacing of the contours in the x-axis direction.

Temperatures for each height for each timestep from Array 1 (Palmerston North)



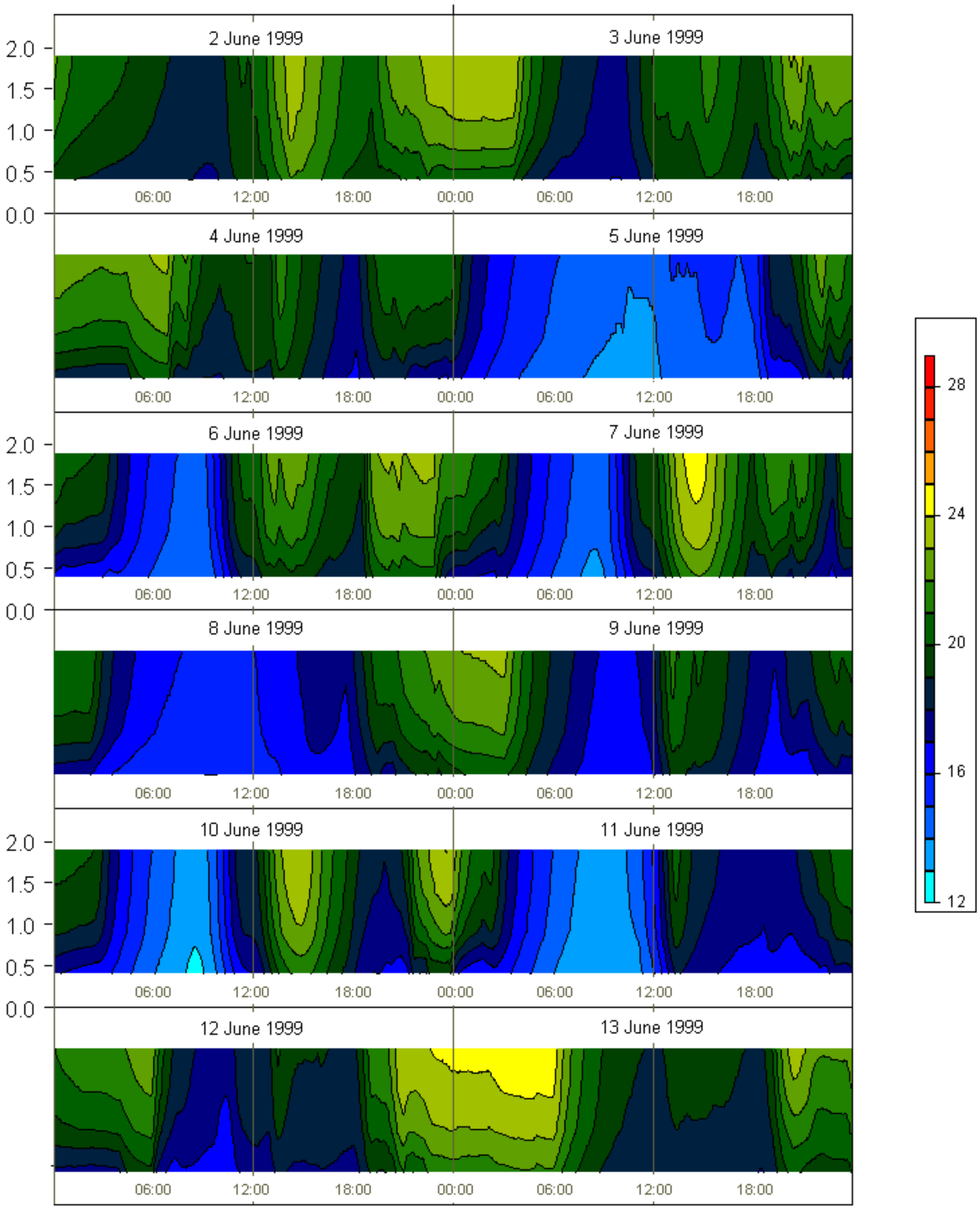


Figure 5.18 Temperature-height-time colour contour for array 1 (Palmerston North southwest corner)

Examining the contours of Figure 5.18 reveals information on the impacts of the heating methods on the temperature distribution within the room. The increase in room temperatures in the afternoon is due to solar gains through the north facing glazing. The shape of the temperature increase is 'stalactite' in shape having up to a 4°C increase across the 1.5 m height difference at maximum temperature. The gas heater produces a similar range of temperatures in the evenings (up to 4°C across 1.5 m) however it is not always consistent presumably due to changes in the occupant's behaviour. One behavioural characteristic of the occupants of the Palmerston North house is that the heater is frequently operating into the early hours of the morning.

The temperature-height profiles for a number of measurements from array 1 (southwest corner) and array 2 (northwest corner) for the 2nd June 1999 are shown in Figure 5.19. The curvature of the profiles from array 1 and array 2 are similar however array 2 has only three measurement points and the temperatures are slightly lower in value than the temperatures from array 1. The temperature at 0.9 m on array 2 may be reduced by the placement of a chair shielding this sensor from the direct path of the heater.

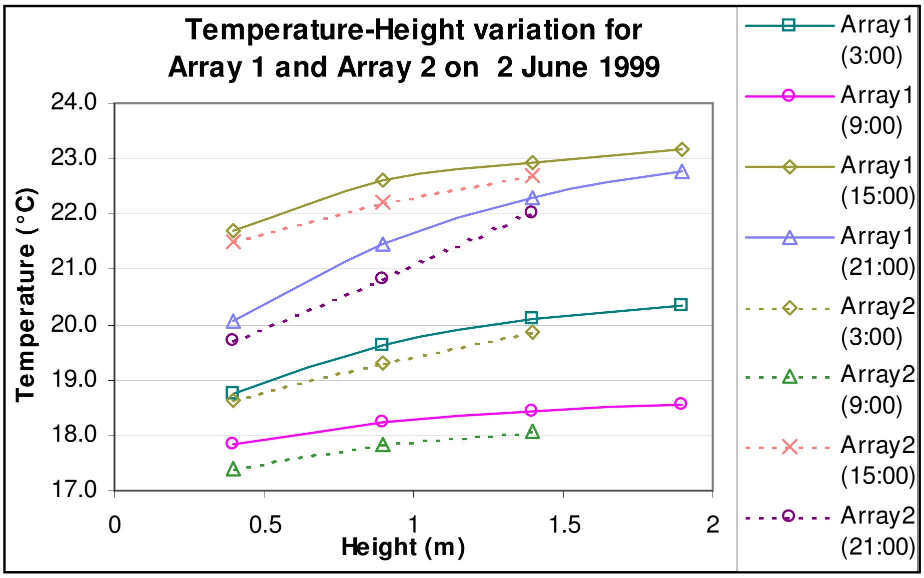
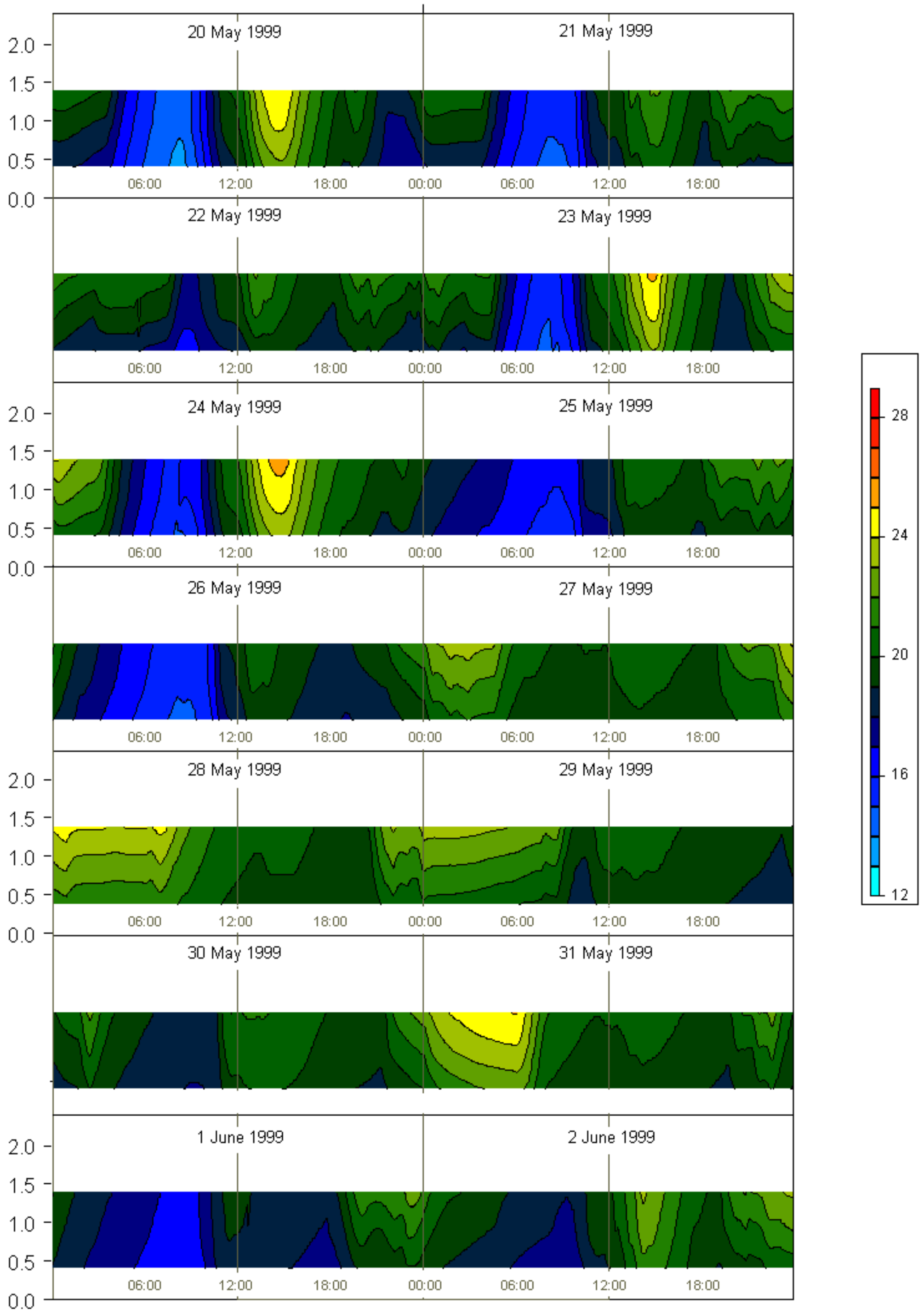


Figure 5.19 Temperature-height comparison for array 1 (southwest corner) and array 2 (northwest corner)

Figure 5.20 gives the temperature-height-time graph of the data from array 2, which shows a very similar pattern to the bottom two-thirds of temperature-height-time graph from array 1 shown in Figure 5.18.

Temperatures for each height for each timestep from Array 2 (Palmerston North)



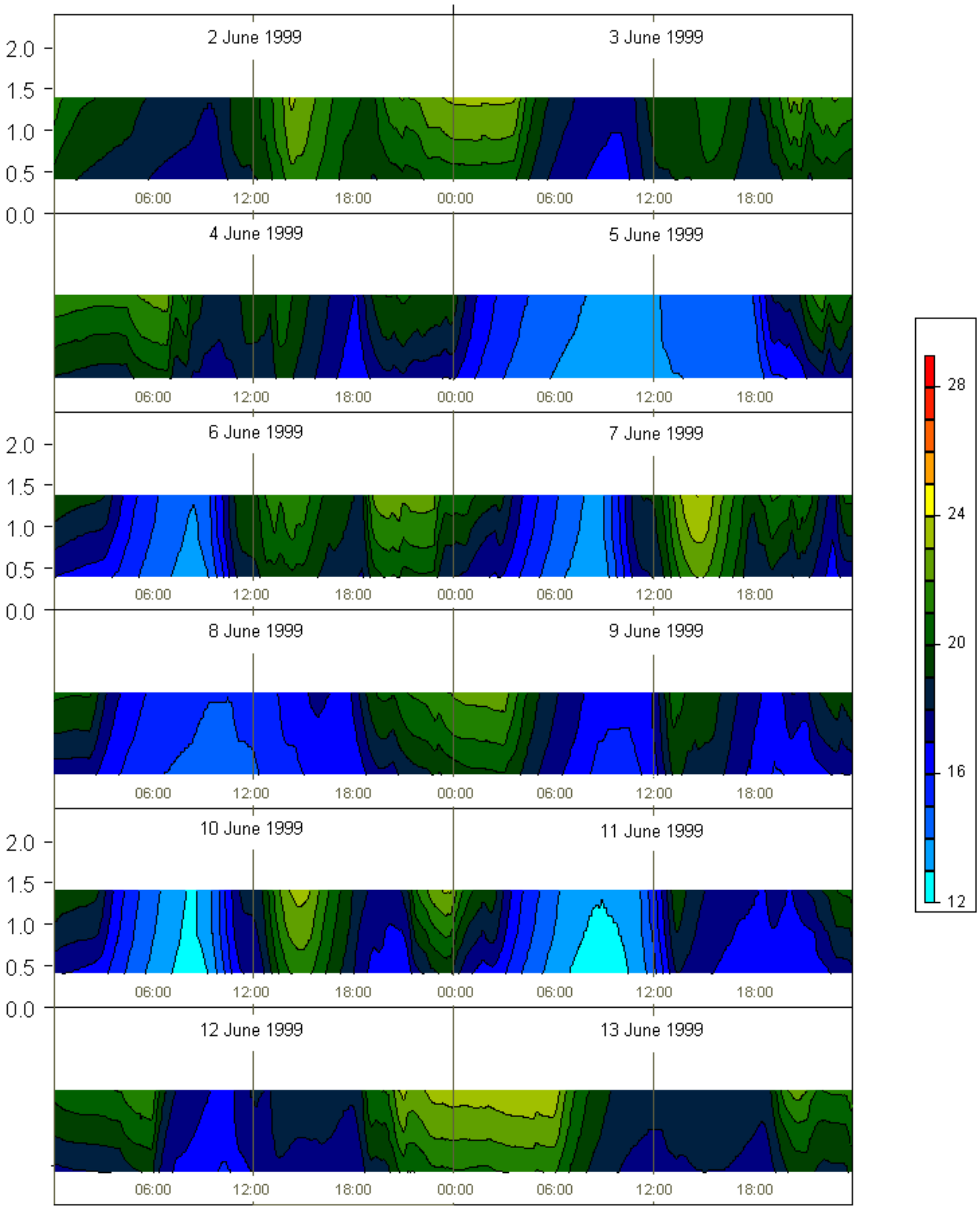


Figure 5.20 Temperature-height-time colour contour for array 2 (Palmerston North northwest corner)

To see to which extent the vertical temperature distributions vary between houses, summer and winter vertical temperature distributions were also collected from the Whitby house so that they could be compared with the Palmerston North data.

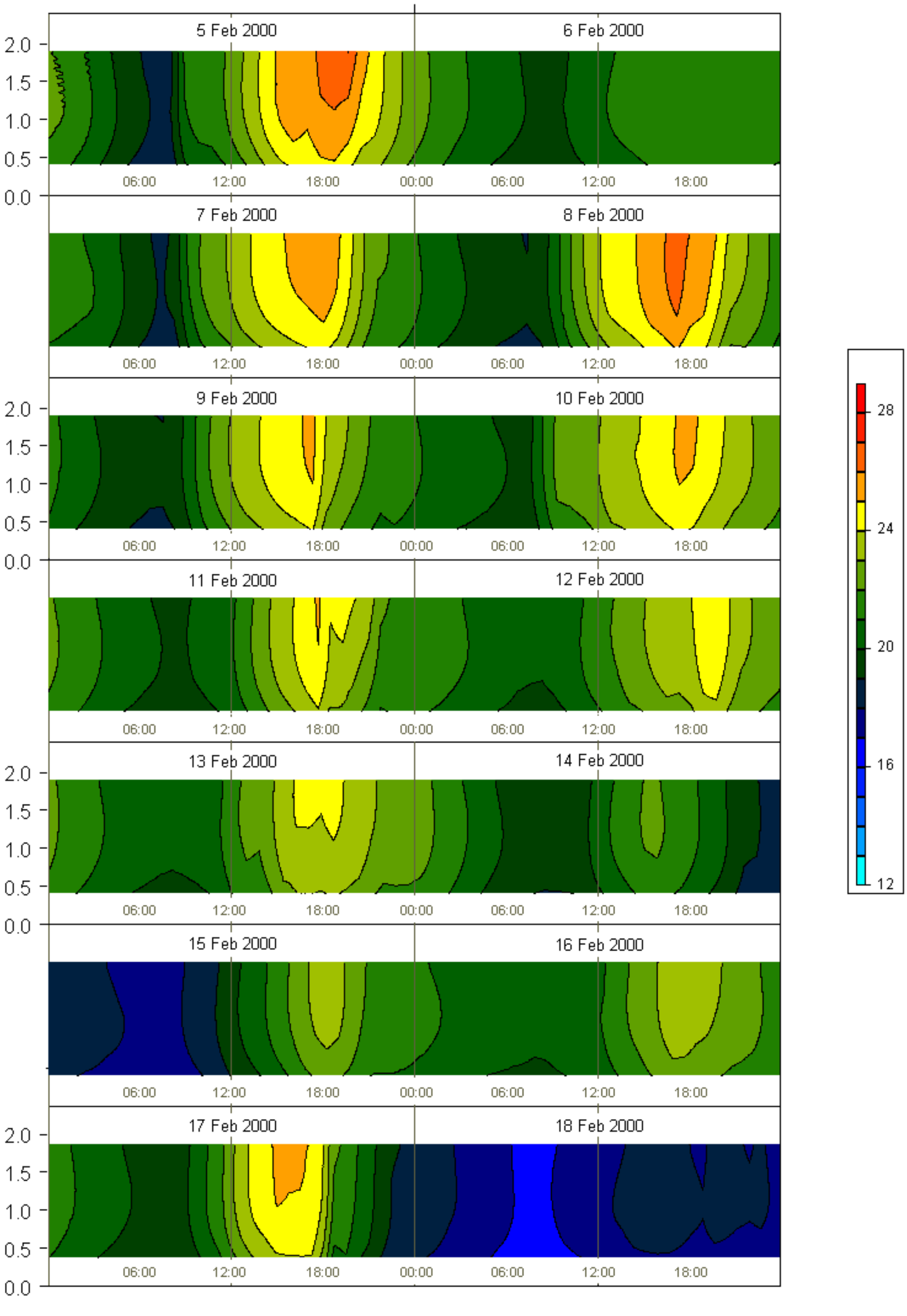
Figure 5.21 shows the temperature-height-time graph for the summer Whitby data. For this data it was necessary to interpolate the vertical temperature profile to 0.1 m spacings for each time step in order for the graphing program (`S-PLUS`) to graph the data without anomalous ridgelines. A residual of this interpolation process can be seen as the wavy contour lines at the start of the data (5th February 2000) in Figure 5.21.

The colouring of Figure 5.21 is predominantly in the green range (comfortable temperatures, 19°C to 24°C). The shape of the temperature increases are not strictly tapered, as was the case for Palmerston North, with bulging occurring at intermediate heights (1.0 m - 1.5 m). The vertical temperature differences are also less pronounced with differences of less 2°C across the 1.5 m change in height at any one instant in time. The temperature increases due to the solar gains are also broader than those observed for Palmerston North, presumably due to the longer summer sunshine hours.

The most striking contrast in the winter Whitby temperature-height-time graph (shown in Figure 5.22) is that the colouring is quite different due to the cooler temperatures recorded. The temperatures are predominantly in the blue (13°C to 19°C) and cyan (9°C to 13°C) ranges with the colour legend needing to be extended down to 6°C to cover the range of temperatures encountered. The bulging seen for the summer data is not visible within the winter data. The vertical temperature differences remain small (less than 2°C across the 1.5 m height of the temperature array) except for specific evenings periods when the heater operation results in vertical temperature differences of 5°C to 6°C across the 1.5 height of the temperature array. The heating on the 15th June 2000, after two days of cold temperatures, produced a vertical temperature difference of up to 9°C.

The resulting temperatures during the winter solar gains in the Whitby house are not as high as the temperatures achieved during solar gains for the Palmerston North house. There may be a number of reasons for this; one being that the temperatures from the Whitby house are colder before the afternoon solar radiation. Another reason is the Whitby house orientated along a north-south axis and has a smaller amount of north facing glazing, which is more obstructed by surrounding buildings and other objects than is the case for the Palmerston North house.

Temperatures for each height for each timestep from the Whitby Array (Summer)



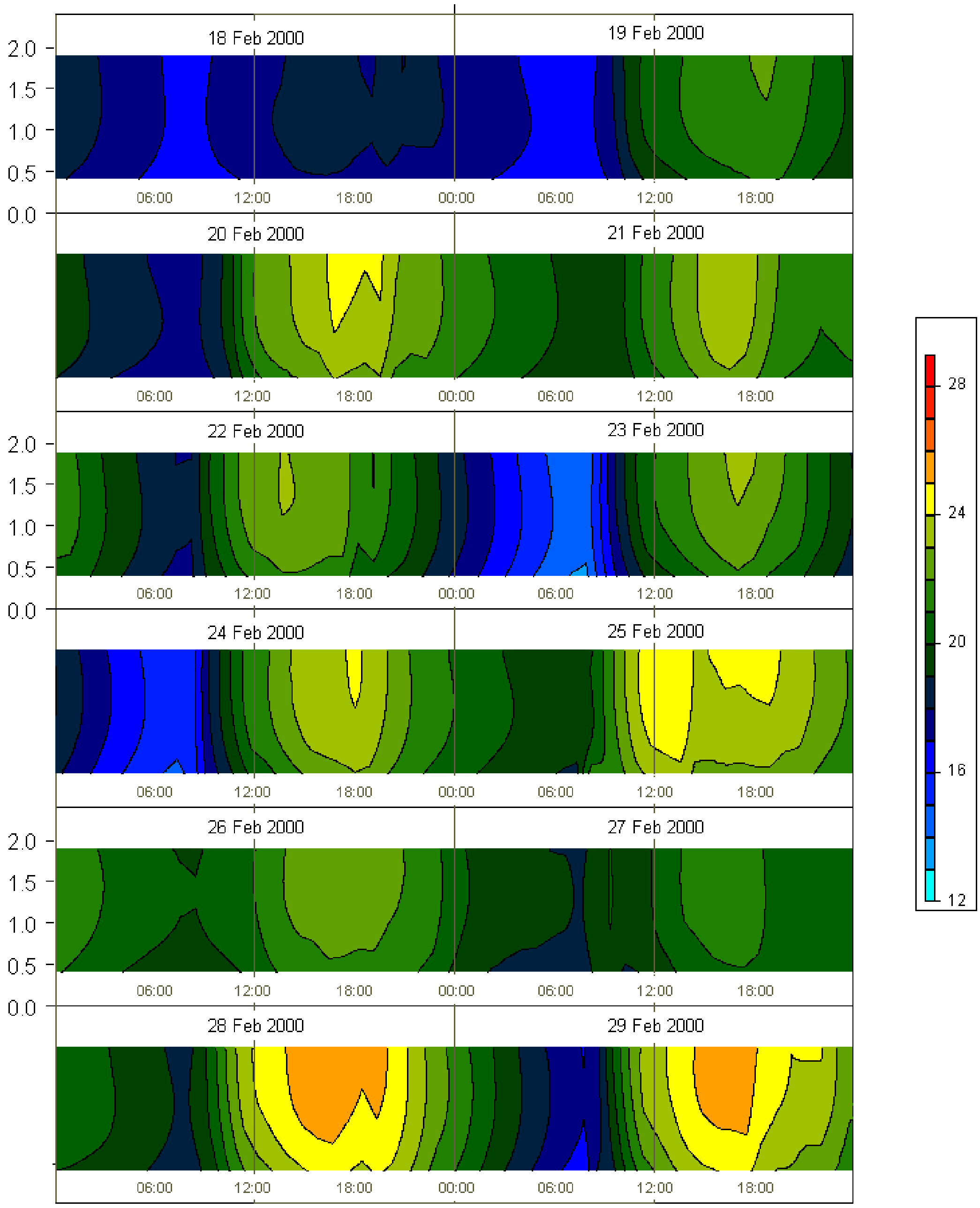
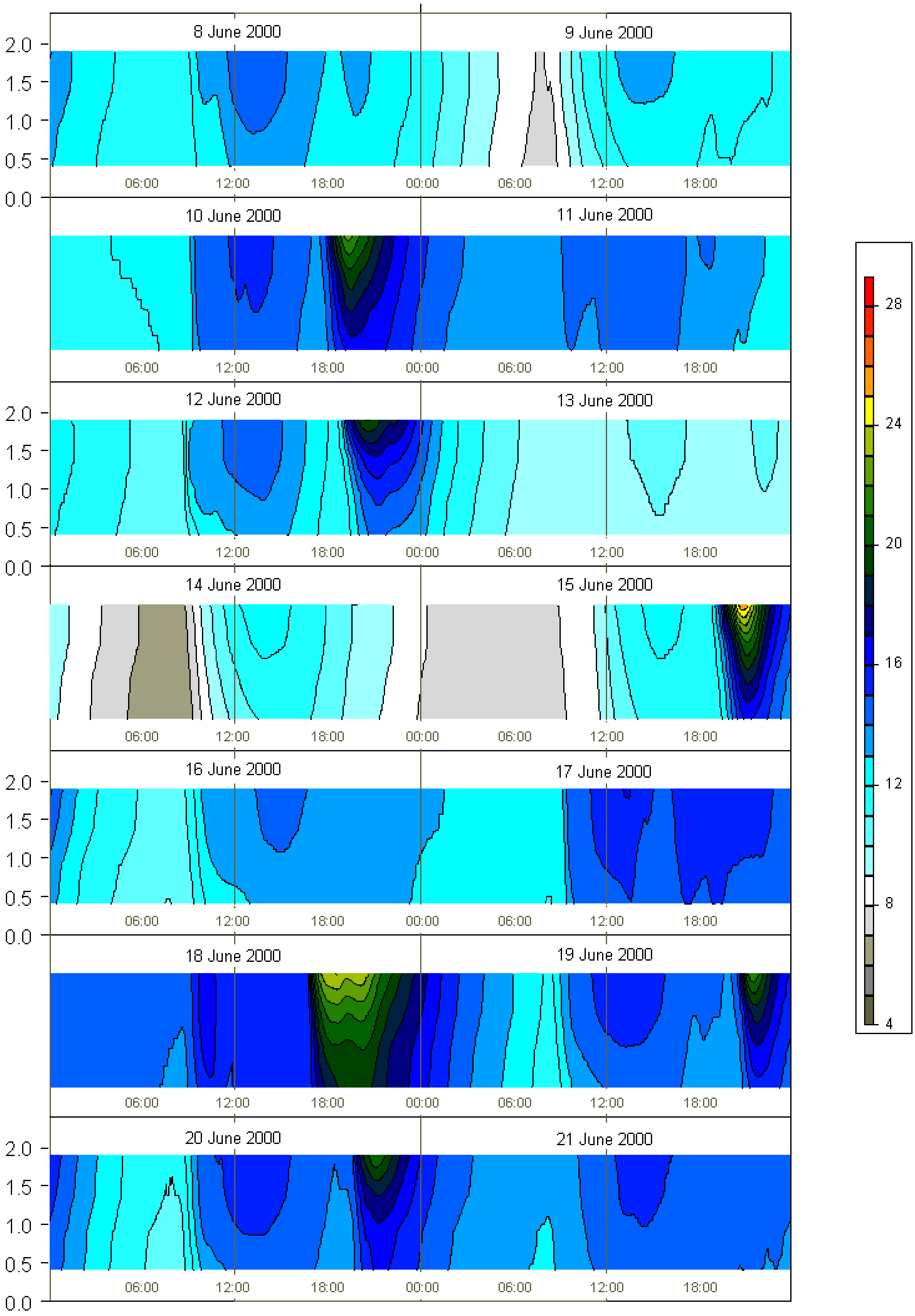


Figure 5.21 Temperature-height-time colour contour for the summer Whitby array

Temperatures for each height for each timestep from the Whitby Array (Winter)



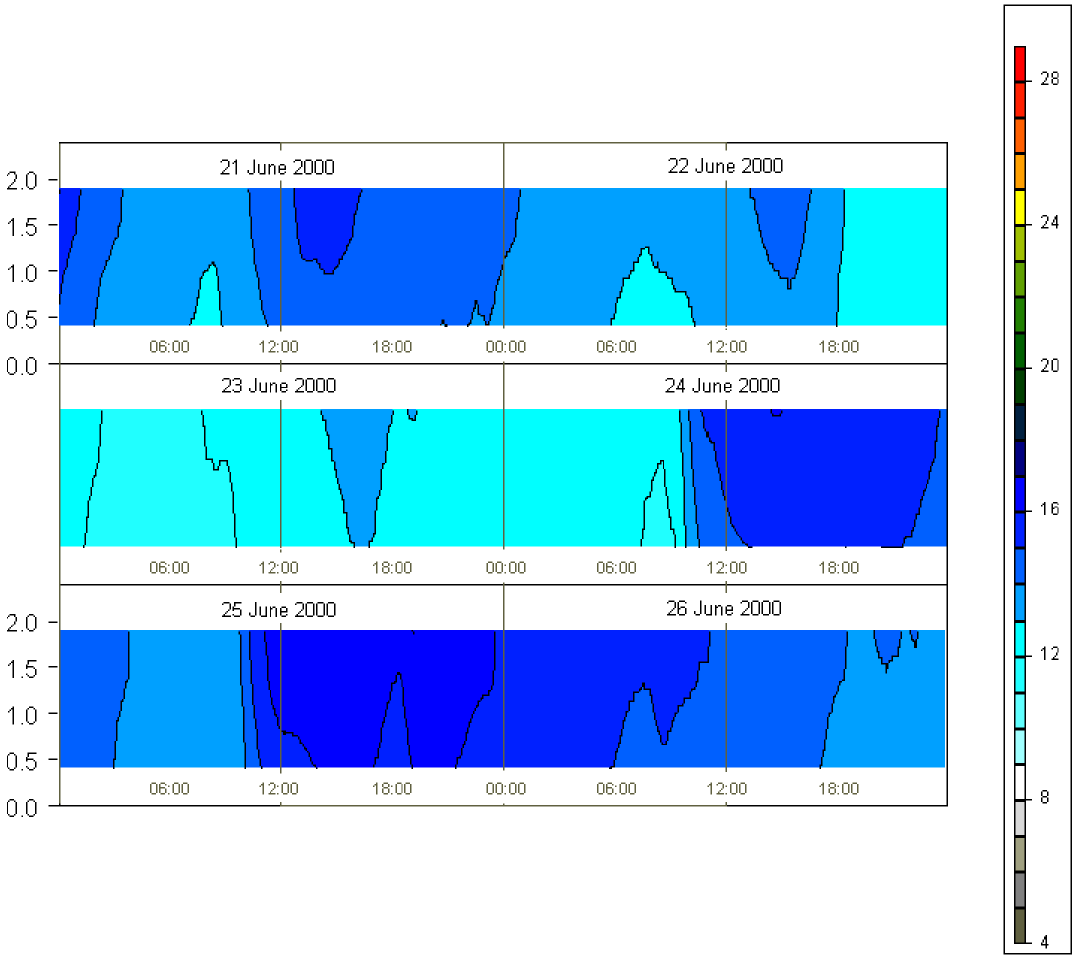


Figure 5.22 Temperature-height-time colour contour for winter Whitby array

In order to examine the linkages between the vertical temperature distribution and other parameters, a mathematical description of the vertical temperature distribution will first be considered.

5.5 Mathematical Description of the Vertical Temperature Distribution

The temperature-height-time graphs of Array 1 from Palmerston North (Figure 5.18) and the summer and winter Whitby arrays (Figure 5.21 and Figure 5.22) were each determined from four temperature loggers that were vertically spaced 0.5 m apart. The measured temperatures approximate the true vertical temperature distribution with four degrees of freedom. If the vertical temperature distribution permits a low degree of freedom function (say a two-parameter function) to describe the room temperatures then a smaller number of loggers, placed at different heights, could characterise the vertical temperature distribution.

Before a number of two-parameter functions are examined, a quadratic function will be firstly examined to determine how well a three-parameter function fits the data from the array in Palmerston North as well as the two sets of measurements from the array in Whitby.

$$T = q_0 + q_1 Z + q_2 Z^2 \tag{6.1}$$

In order to reduce the computational processing, a random 5% sample (360 cases) of the instantaneous temperature-height for each dataset was made. Least squares fits were then made for each of the sampled cases. The coefficient of determination was calculated for each fit and the mean coefficient of determination calculated for all of the cases in the sample. Table 5.5 shows, this mean coefficient of determination for the quadratic function for each of the three datasets.

Table 5.5 Mean coefficient of determination (R^2) for a quadratic fit for a randomly selected 5 % of the data.

Equation Name	**Formula**	**Coefficient of Determination (R^2)**		
		Palmerston North	**Whitby (Summer)**	**Whitby (Winter)**
Quadratic	$T = q_0 + q_1 Z + q_2 Z^2$	.995	.989	.977

It may be expected that two-parameter functions will not fit as well as the three-parameter quadratic function. A series of two-parameter functions were examined and Table 5.6 shows for each of the three datasets, the mean of the coefficient of determination for each two-parameter function examined. While particular functions show reasonable fits for particular datasets there is no function that has consistently high values for the mean coefficient of determination for all three datasets.

Table 5.6 Mean coefficient of determination (R^2) for two-parameter functions for a randomly selected 5% of the data. Shading indicates the highest mean coefficient of determination for each dataset.

Equation Name	**Formula**	**Coefficient of Determination (R^2)**		
		Palmerston North	**Whitby (Summer)**	**Whitby (Winter)**
Linear	$T = b_0 + b_1 Z$	.921	.641	.942
Square	$T = b_0 + b_1 Z^2$	.797	.471	.875
Reciprocal	$T = b_0 + \frac{b_1}{Z}$	.971	.910	.832
Exponential	$T = b_0 + b_1 \mathrm{e}^{-Z}$	.988	.807	.933
Square Root	$T = b_0 + b_1 \sqrt{Z}$	.967	.732	.946
Reciprocal Square Root	$T = b_0 + \frac{b_1}{\sqrt{Z}}$	.989	.872	.884
Logarithmic	$T = b_0 + b_1 \ln Z$	.990	.812	.926

As the quadratic function fitted the data well, this function will be re-examined with the view of making specific simplifications to reduce the number of dependent parameters within it. Firstly the quadratic function is re-expressed as

$$T = c_0 + c_2 (Z - c_1)^2 \tag{6.2}$$

The advantage of the form of equation (6.2) is that the coefficients c_0, c_1 and c_2 have meanings that can be applied to the vertical temperature distribution; c_1 is the height at which the indoor temperature is a maximum (or a minimum), c_0 is the temperature at this height and c_2 is a measure of the curvature of the vertical temperature distribution. In order to reduce this function back down to a two-parameter function, one of the values of c_0, c_1 or c_2 need to be fixed. It was seen in Section 5.4 that the curvature (c_2) and height (c_0) of the vertical temperature distributions are dynamic so c_1 was chosen as the parameter to fix. The function therefore becomes

$$T = c_0 + c_2 (Z - h)^2 \tag{6.3}$$

where the value h is the fixed value of c_1 but could still be different for each dataset.

To select values for *h,* a series of least squares fits (whose mean coefficient of determination is shown in Table 5.7) were made with differing values of *h*. The range of values for *h* were initially taken between 0.5 and 2.4 however for the winter Whitby data the fitting seemed to improve with height so values of up to 3.4 were used for *h* for this case. As both buildings have a flat ceiling at a height of 2.4 m the physical meaning of *h* as the height maximum temperature is not appropriate.

Table 5.7 Mean coefficient of determination (R^2) for the modified quadratic function (equation (6.3)) for a series of values for *h*.

h	**Coefficient of Determination (R^2)**		
(m)	**Palmerston North**	**Whitby (Summer)**	**Whitby (Winter)**
0.5	0.683	0.332	0.793
0.6	0.632	0.286	0.753
0.7	0.560	0.227	0.693
0.8	0.454	0.154	0.599
0.9	0.301	0.075	0.451
1.0	0.109	0.039	0.233
1.1	0.007	0.186	0.038
1.2	0.216	0.558	0.114
1.3	0.563	0.847	0.398
1.4	0.789	0.943	0.627
1.5	0.899	0.947	0.760
1.6	0.951	0.924	0.834
1.7	0.974	0.896	0.877
1.8	0.985	0.869	0.902
1.9	0.989	0.846	0.918
2.0	0.990	0.826	0.929
2.1	0.989	0.810	0.936
2.2	0.987	0.795	0.940
2.3	0.985	0.783	0.944
2.4	0.983	0.772	0.946
2.5	-	-	0.948
2.6	-	-	0.949
2.7	-	-	0.950
2.8	-	-	0.951
2.9	-	-	0.952
3.0	-	-	0.952
3.1	-	-	0.952
3.2	-	-	0.952
3.3	-	-	0.952
3.4	-	-	0.952

To further examine the fitting of the modified quadratic equation (6.3) it is useful to rewrite the quadratic equation (6.1) in the form of equation (6.3),

$$T = \left(q_0 - \frac{q_1^2}{4q_2} \right) + q_2 \left(Z + \frac{q_1}{2q_2} \right)^2 \tag{6.4}$$

so comparing (6.3) with gives

$$c_0 = \left(q_0 - \frac{q_1^2}{4q_2} \right) \tag{6.5}$$

$$c_2 = q_2 \tag{6.6}$$

$$h = -\frac{q_1}{2q_2} \tag{6.7}$$

The time series of $h = -\frac{q_1}{2q_2}$ will give an indication of the suitability of the fit. A quadratic fit was made for each of the datasets, the height of maximum temperature *h,* was then determined for each of the Palmerston North, summer Whitby and winter Whitby data sets and is then graphed in Figure 5.23, Figure 5.24 and Figure 5.25 respectively.

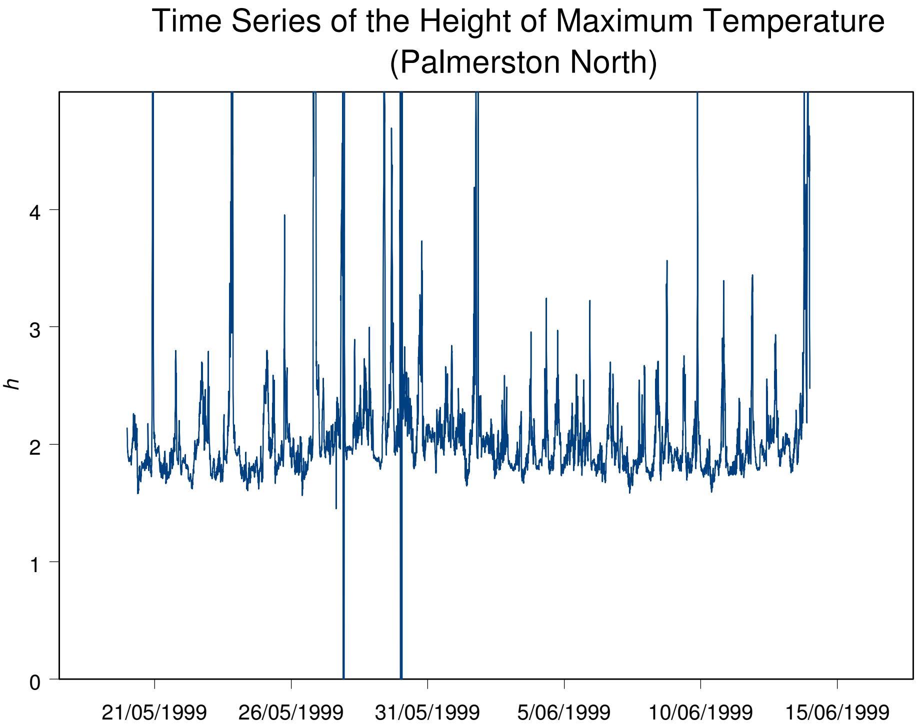


Figure 5.23 Height of maximum temperature for Palmerston North

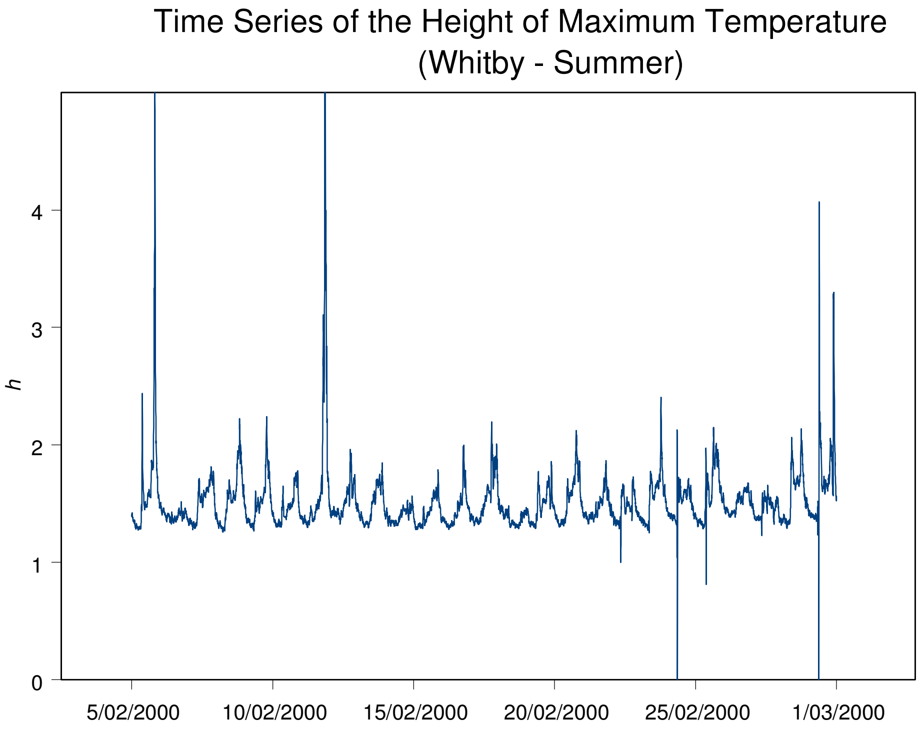


Figure 5.24 Height of maximum temperature Whitby Summer

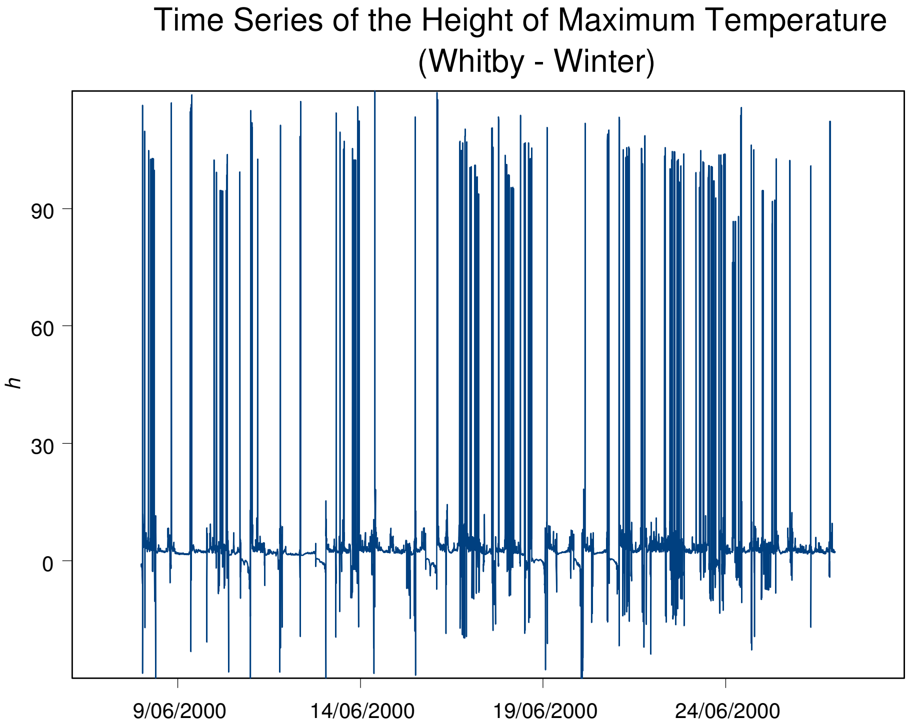


Figure 5.25 Height of maximum temperature Whitby Winter (scale extended)

While the value of $h = -\frac{q_1}{2q_2}$ looks settled for the Palmerston North and summer Whitby data, the winter Whitby data appears to have an instability in the fitting process; while the data appears to have a background value for h of around 2 there are occasional spikes of very high (non-physical) values. Figure 5.26 shows again the time series plot of the height of the maximum temperature for the winter Whitby data but with the data subsetted by the concurrent value of the curvature of the fitting equation, c_2. This subsetting is done by selecting ranges for the curvature parameter c_2 so that each subset has an equal number of values within them (1200 data points). It can be seen that the breakdown of the fitting procedure occurs when the curvature of the fitted line is close to zero. Relating this back to the physical processes involved, the ability to model the vertical temperature distribution is dependent on a difference in temperatures at different heights. When the temperatures are not significantly different, the fitting procedure does not work well. This situation also contrasts the two example buildings - while the Palmerston North house is heated regularly the fitting is well behaved whereas for the occasional winter heating in the Whitby house the fitting is more temperamental.

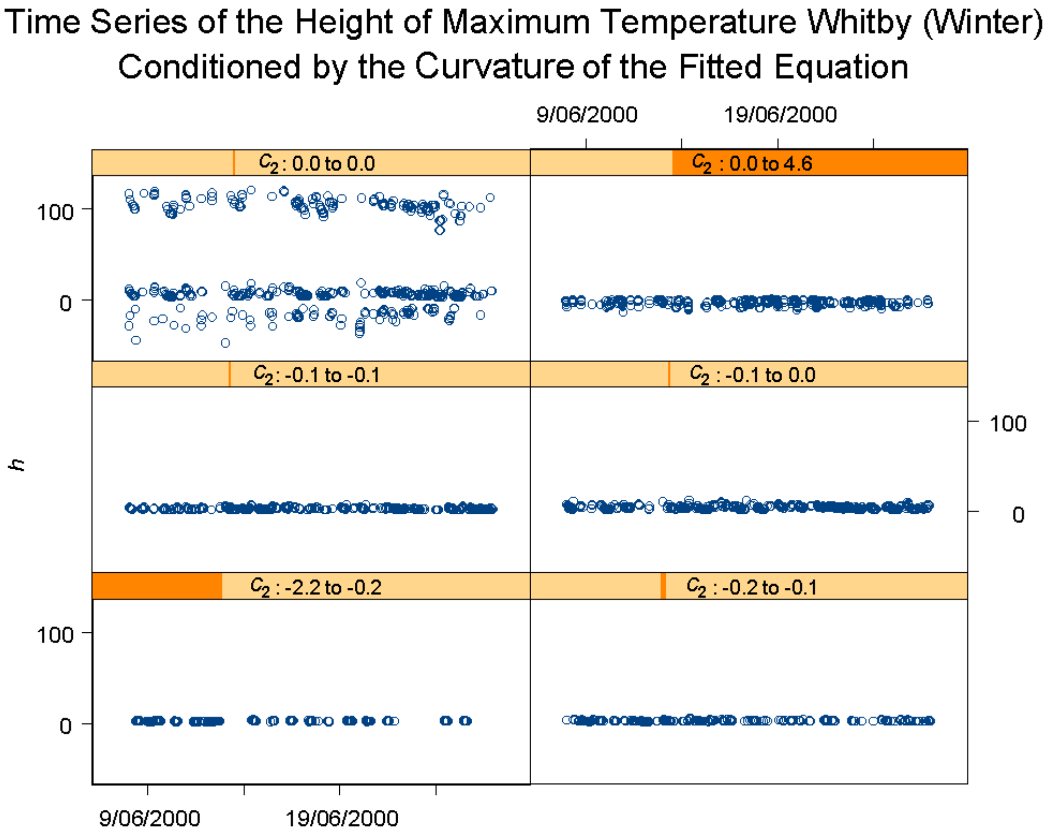


Figure 5.26 The height of maximum temperature subsetted by the fitted coefficient c_2

The winter Whitby data appears to be distinct from the Palmerston North and summer Whitby data in that an optimum value of h is not well defined. As h becomes greater than 2 the mean coefficient of determination continues to improve, however the physical meaning of h is lost once it exceeds 2.4. For the further analysis of the vertical temperature distribution a value for h of 2 was taken (matching the Palmerston North data) to reflect the background behaviour of this parameter. Table 5.8 gives the properties of fitted functions used.

Table 5.8 Properties of the fitted functions used.

Property	**Palmerston North**	**Whitby (Summer)**	**Whitby (Winter)**
R^2	.990	.947	.929
h	2.0	1.5	2.0

In fitting functions to data, it is sensible to examine the residuals of the fitted function to the measured data. The residuals, in this case, are reasonably well behaved and details are given in Appendix D.

More work is required on understanding the height of maximum temperature, h. This parameter is not constant between different houses or even constant within the same house; differing from summer to winter in the Whitby house. Analysis of this parameter h may require more careful consideration of ventilation and boundary effects (presence of insulation) and will be left for future research.

5.6 Drivers of the Vertical Temperature Distribution

The parameters determined from the fitted functions are c_0, the temperature at a particular height (h, height of maximum temperature) and c_2, a value of curvature of the vertical temperature distribution. To examine why these parameters vary, hourly values from the Palmerston North data of c_0 and c_2 (when h was set to 2) were compared alongside the temperature at the centre of the room (T14), the output of the temperature sensor placed on the heater (TT26964), a dichotomous indicator of whether the heater was on or off (light blue circles represent heater on, dark blue squares indicate when the heater was off) as well as the external temperature and the global horizontal solar radiation recorded by the nearest automatic weather station (NIWA Agent Number 3243).

Scatter plots of one variable against another are informative to examining relations. Figure 5.27 gives a matrix plot of all of the scatter graphs of the parameters under investigation.

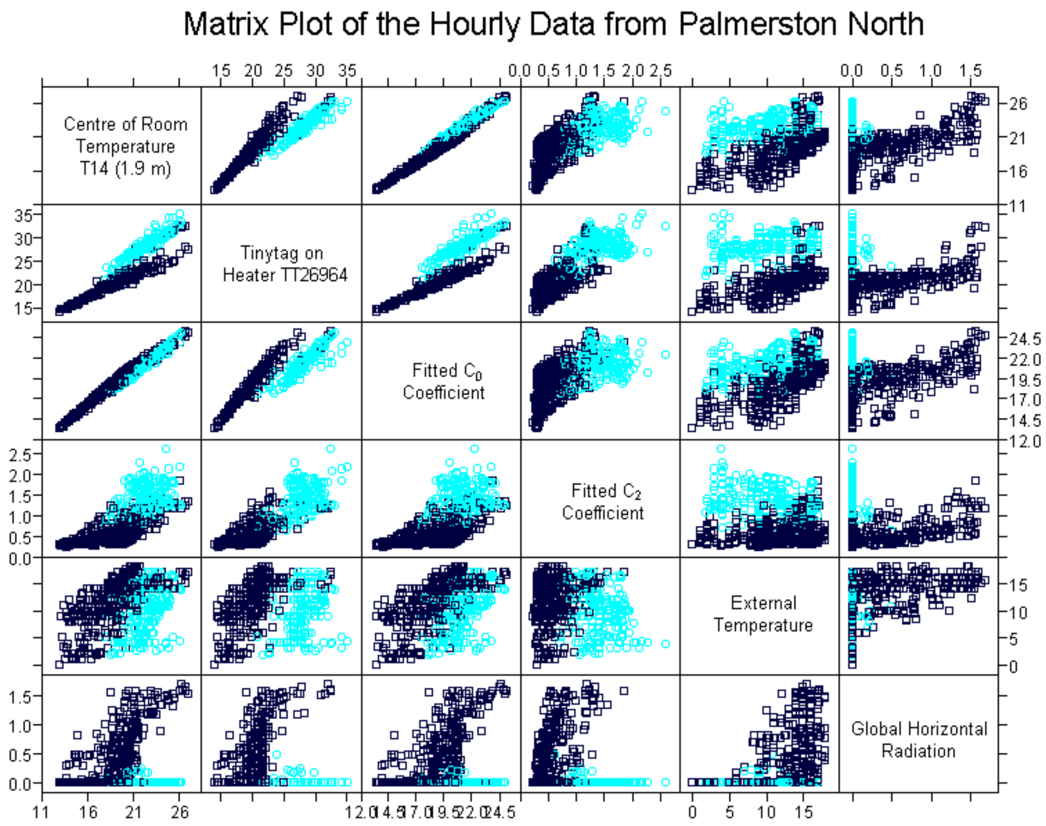


Figure 5.27 Matrix plot of hourly data from Palmerston North including the fitted coefficients, the centre of the room temperature, the output of the logger placed on the heater and the temperature and global horizontal radiation recorded by the nearest automatic weather station. (light blue circles represent heater on, dark blue squares indicate heater off)

The strongest relationship seen in Figure 5.27 is between the fitted coefficient c_0 and the centre of room temperature measurement (T14), which has a correlation coefficient of 0.985. This is not unexpected as c_0 will estimate the temperature within the room at a height of 2.0 m (from the value of h set in Table 5.8) and as the centre of room temperature is measured at 1.9 m these two values are similar.

The curvature coefficient c_2 from the fitted relationship has a more obscure interpretation. Table 5.9 gives the correlation coefficient of the curvature c_2 of the fitted equation with other parameters measured. Table 5.9 indicates that the curvature coefficient c_2 has it highest correlations with the temperature logger placed on the heater and the indicator of whether the heater was on or off. It is perhaps better to work with the heater on/off indicator as the temperature logger placed on the heater has a composite output that is difficult to interpret. Either way the curvature has a high value when heating is taking place. It was decided to generalise this to model all heat flow into the room rather than just from the gas heater.

Table 5.9 Correlation coefficients for the curvature c_2 with other parameters for Palmerston North

	Correlation Coefficient with c_2
Centre of room (T14)	0.736
TT26964	0.838
Heater Indicator	0.809
Fitted value of c_0	0.630
Ext. Temperature	-0.158
Solar Radiation	-0.145

Four of the major heat flows into the room are

1. from the gas heater
2. from solar gains through the windows
3. from heat conduction through the walls of the room.
4. due to ventilation

The heat flow due to the heater was taken to be constant when the heater was on. The heat flow due to solar gains were taken as proportional to the global horizontal radiation as recorded by the automatic weather station. The heat flow through the walls and the heat flow due to ventilation are dependent on the temperatures within the room, within adjoining rooms and outside of the house. To simplify the heat flow due to these processes, the heat flow will assumed to be proportional to the difference between the indoor and outdoor temperature.

The independent variables used in the linear regression model were therefore a dichotomous indicator of whether the heater is on or off (H), the global horizontal radiation (R) and the temperature difference between the indoor temperature and the outdoor temperature (T_{i-o}). Table 5.10 gives the coefficients of the fitted values for the model.

Table 5.10 Coefficients for the linear model fit of the curvature c_2 from Palmerston North

Term	**Value**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	0.2412	0.0284	8.4972	0
H	0.7746	0.0293	26.4704	0

R	0.2855	0.0263	10.8414	0
$T_{i\text{-}o}$	0.0320	0.0032	10.1639	0

This model improves the coefficient of determination (square of the correlation coefficient for a single variable) from 65% from the simple correlation of c_2 with the heater on/off indicator to a multiple coefficient of determination of 74% when the heater on/off (H), solar radiation (R) and temperature difference variables ($T_{i\text{-}o}$) are introduced.

A similar process to that used for Palmerston North will be applied to the winter data from Whitby. The summer Whitby data will not be considered as the heat flows for summer would not be as large as those of winter. Unfortunately the nearest automatic weather station was located some distance away in Paraparaumu (NIWA agent number 8567), about 23 km north of Whitby. Figure 5.28 shows a matrix plot of the hourly data from Whitby (Winter).

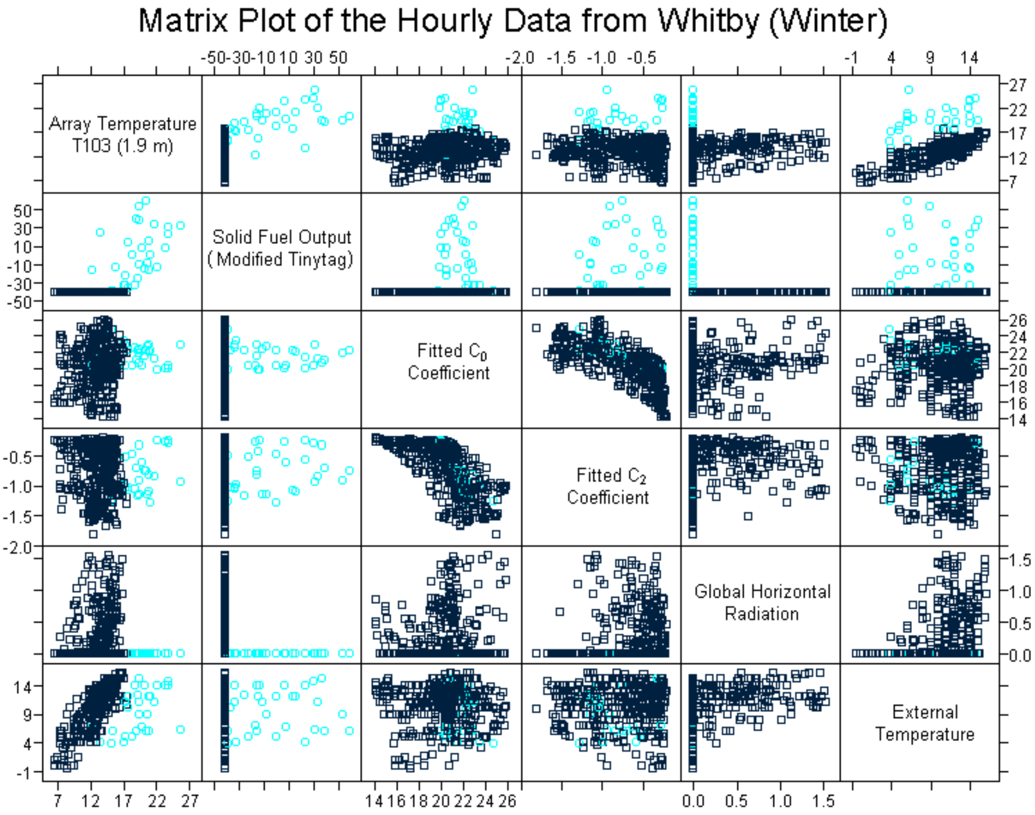


Figure 5.28 Matrix plot of hourly winter data from Whitby including the fitted coefficients, the temperature at the top of the array, the output of the modified Tinytag Logger attached to the Woodburner and the global horizontal radiation and temperature recorded by automatic weather station, NIWA agent number 8567.

Examining Figure 5.28 shows that the Whitby data is more scattered than for the Palmerston North data. The intercept term does not correlate well with the air temperature at 1.9 m, as was the case for the Palmerston North data. The Individual correlation coefficients for the curvature coefficient are given in Table 5.11 and show that all the correlations are small. The largest correlation, other than with the other fitted coefficient c_0, is with the solar radiation.

Table 5.11 Correlation coefficients for the curvature c_2 with other parameters for the winter Whitby data

	Correlation Coefficient with c_2
Array Temp (T103)	-0.038
Solid Fuel Logger	0.012
Heater Indicator	-0.022
Fitted Value c_0	-0.687
Ext. Temperature	0.021
Solar Radiation	0.195

To make a direct comparison with the heat flow model used for Palmerston North a similar linear model was used. The independent variables in this model were an indicator variable of when the heater was on or off (H), the solar radiation as measured by NIWA agent 8567 (R), and the temperature difference between the inside air temperature and the external temperature as measured by NIWA agent 8567 (T_{i-o}). The coefficient of determination for this model was 4%, which is a very low value. Consequently the model does not describe well the values of the curvature of the vertical temperature distribution c_2 which it self were poorly defined (see section 5.5).

The two buildings are contrasting; while the Palmerston North house has large heat flows the Whitby house has only small heat flows. These differences are due to;

- more frequent use of heating in Palmerston North house
- the Palmerston North house being more compartmentalised in design that the Whitby house
- lower levels of insulation levels in the Palmerston North house
- more North facing glazing in Palmerston North

Consequently the vertical temperature distribution in the Palmerston North house is well defined with the curvature of the distribution able to be related to the sources of heat input into the room.

On the other hand the vertical temperature distribution for the Whitby house during winter is not well defined and the statistical comparison of the curvature of this distribution does not clearly relate to the heat input variables into the room.

5.7 Localised Temperature Differences Around the Room

In Section 5.2, the differences in temperatures from temperature loggers placed at different heights was seen to be an identifiable pattern. This section will use the temperature measurements from approximately the same height from around the living room in the Palmerston North house to see if there are additional sources of temperature variation within the room and look to see if these variations can be explained.

Table 5.12 gives the difference in the mean temperatures from each of the two temperature arrays located in the northwest and southwest corners of the room. It appears that the northwest array is approximately 0.3°C cooler than the array in the Southwest corner.

Table 5.12 Difference between temperature array in northwest corner and the temperature array in the southwest corner

Height (m)	Temperature Difference (°C)
0.4	-0.24
0.9	-0.47
1.4	-0.35

Figure 5.29 and Figure 5.30 show floor plans of the living room annotated with the difference in temperature between the logger shown and the logger of approximate corresponding height in the southwest array (T3 (0.9 m) for Figure 5.29 and T6 (1.9 m) for Figure 5.30).

Figure 5.29 gives the temperature differences for loggers at a height of 0.9 m and shows that the temperature of the southwest corner appears to be warmer than the northwest corner or the east wall. Both the north and east walls are external walls so temperatures near these walls can be expected to be lower. The southwest corner also could also be warmer due to the electric hot water cylinder and the refrigerator-freezer being nearby but separated by internal walls.

Figure 5.30 again shows the north and east walls are cooler than the other sensors around the room as is TT26976 on the west wall. The southwest array, centre of room temperature (T14), and T7 are similar in temperature but T8 is higher and T13 is lower in Temperature. The logger T8 is positioned within the wall unit above a stereo unit and other electrical equipment. A refrigerator-freezer is also positioned nearby behind the southern wall. Heat generated from appliances can be appreciable and the warmer temperatures seen by T8 may be due to this heat flow. The temperatures reported by the T13 logger are colder. This may be due to the T13 logger being positioned on a glass-backed shelf giving a path of low thermal resistance to the colder room to the south.

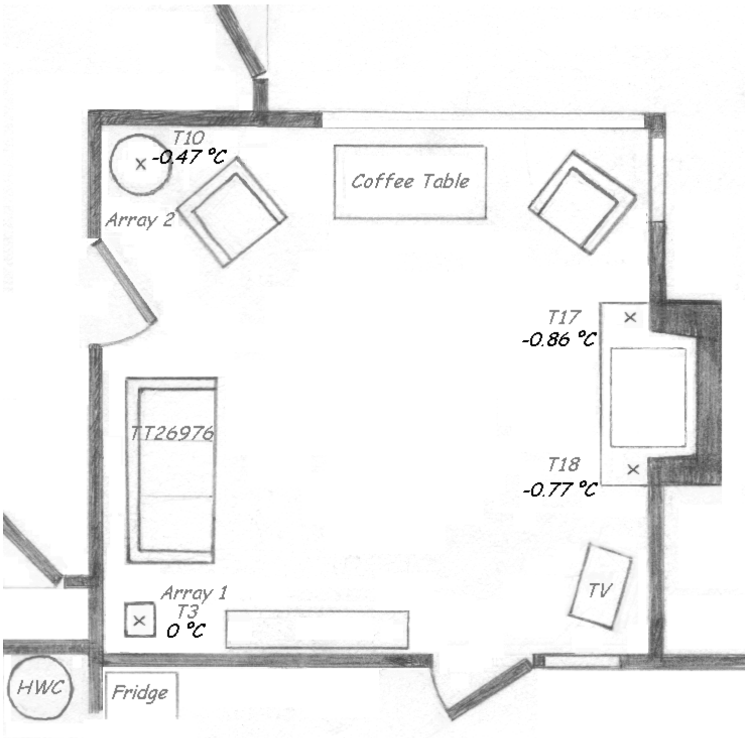


Figure 5.29 Variation in the temperature at a height 0.9 m relative to the southwest array

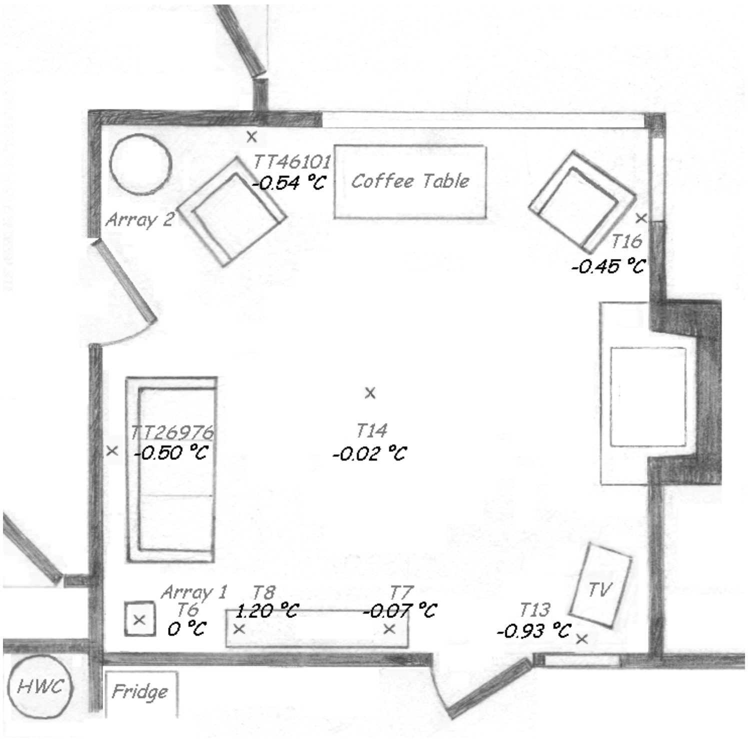


Figure 5.30 Variation in the temperature at a height of either 1.8 m or 1.9 m relative to the southwest array (1.9 m)

The local variations in the temperature within the room appear to have specific causes, such as proximity to heat sources (such as appliances), or pathways of lower thermal resistance (near to exterior walls or glass backed shelves).

It is useful to review other experiences of localised temperature differences. Figure 5.31 shows data from house W26 from the HEEP detailed temperature sample. Figure 5.31 shows three Lounge temperatures and the operation of the television set are shown over 2½ days. The temperature logger 'TempTfrc' was located near the television whereas 'TempTfra' and 'TempTfrb' were located on the other side of the room.

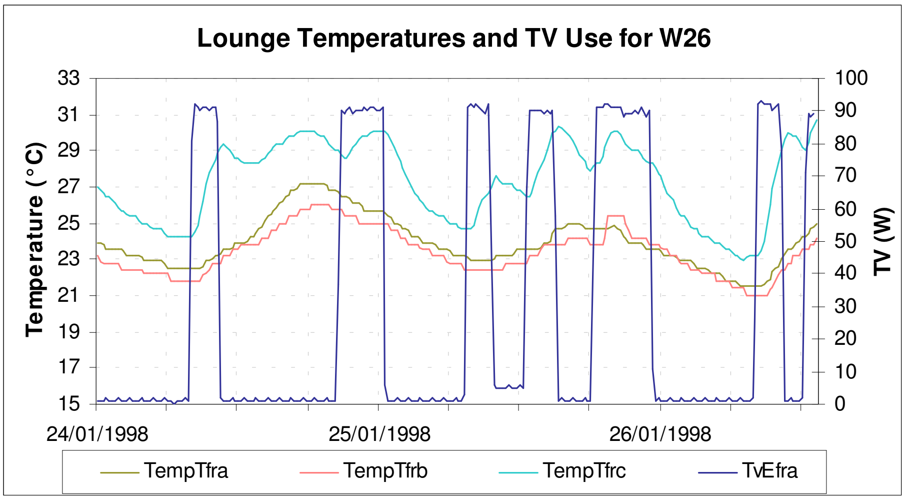


Figure 5.31 Monitored lounge temperatures ('TempTfra', 'TempTfrb' and 'TempTfrc') and TV usage ('TVEfra') for the HEEP detailed temperature sample house W26.

The anomalous elevated temperatures reported by 'TempTfrc' (when compared with 'TempTfra' and 'TempTfrb') coincide with the use of the TV set so when the TV is operating it is also heating the temperature logger 'TempTfrc'.

In Section 3.2 it was seen that a temperature logger placed too close to lights reported elevated temperatures when the light was on. This may be due to the heat from the light or the increased radiant temperature near the light. Section 3.4 stated that the temperature loggers also response to the radiant temperatures so in addition to nearby electrical lighting, other strong radiant heat sources such as solar radiation and high temperature radiant heaters (electric radiant heaters, radiant gas heaters, portable LPG heaters, open fires) should be avoided.

Another source of heat flow is due to air movement within the room. Loggers should not be placed in positions where the air movement is higher than for the rest of the room (near operable windows, doorways, fans or ventilation systems). Draughts also occur close to edges so loggers should be placed away from the ceiling or floor and, where possible, also away from walls.

Lyberg (1993) also provides useful guidance on the placement of temperature loggers.

How these causes affect the temperatures is hard to quantify. The large number of possible influencers and unknown size of each affect makes quantitative analysis difficult. Localised temperature differences may be a non-predictive source of variation and the best course of action may be to ensure that the placement of the temperature loggers minimise the local influences.

5.8 Time Behaviour of the Measurements

So far the temperature measurements within the Palmerston North and Whitby living rooms have only been compared at the same instant in time and no consideration has been given to their time dependence. This section will briefly look at some of the timing issues of the temperatures within the Palmerston North and Whitby living rooms.

Firstly, the time dependence of the indoor temperature will be examined in relation to the driving variables such as the external temperature, the solar radiation and the heat output of the heating systems used.

The external temperature and solar radiation is available as hourly data so the data is first reduced to hourly data. Figure 5.32 gives the average daily profile of the centre of room temperature, the external temperature, the probability of heater operation and the solar radiation received during the previous hour for the Palmerston North data.

For the Palmerston North data, the method used to determine when the gas heater was in operation was to compare the ratio of the absolute temperature of a temperature logger placed on the heater to the absolute temperature of the temperature logger placed at the centre of the room. This method assumes there is no lag between the temperature logger on the heater and the temperature logger at the centre of the room and consequently time delays of the Palmerston North heater were not examined due to this difficulty.

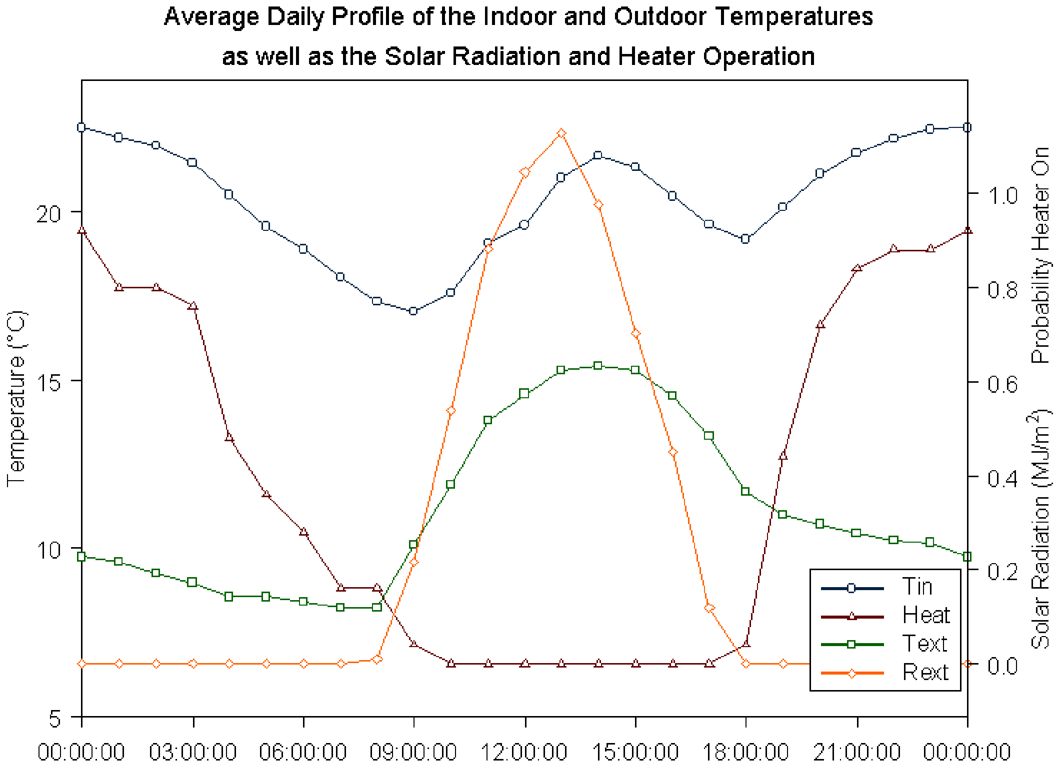


Figure 5.32 Daily profiles for Palmerston North of the centre of room temperature (T14), the likelihood of the heater being on (Heat), the external temperature (Text) and the global horizontal solar radiation received during the previous hour (Rext).

Figure 5.33 gives plots of the auto-correlation and cross-correlation of the centre-of-room temperature with the external temperature and Figure 5.34 gives the auto-correlation and cross-correlation of the centre-of-room temperature with the solar radiation for the Palmerston North data.

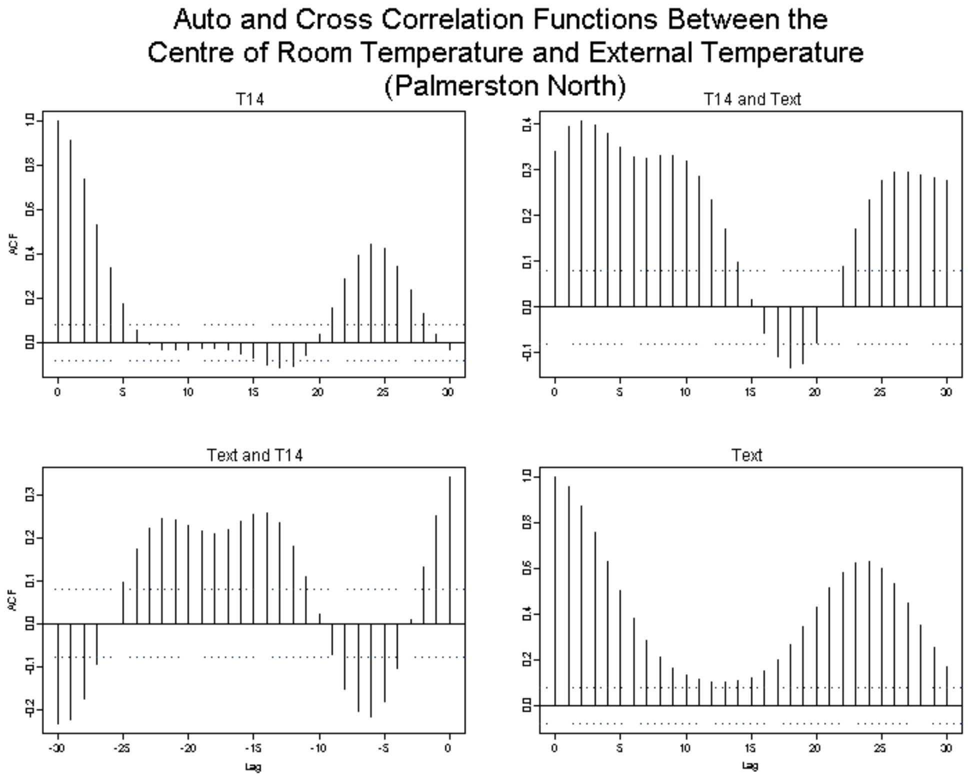


Figure 5.33 The auto-correlations and cross correlation of the hourly centre of room temperature (T14) and the hourly external temperature (Text) for the Palmerston North data. Each lag step is one hour. (see text for description of layout of graphs)

The plots of the auto-correlation functions and cross-correlation function were generated using the `S-PLUS acf` function, which displays the symmetric auto-correlation functions on the main diagonal and the cross-correlation function on the off-diagonals. The non-symmetric cross-correlation function is displayed as separate graphs with positive lags shown above the main diagonal and negative lags below the main diagonal.

The auto-correlation function of the centre-of-room temperature has a value of 0.445 when a 24-hour delay is introduced. This compares to values of 0.624 for the external temperature and 0.767 for the solar radiation indicating that the indoor temperature is the least stable variable for repeatability on a daily basis.

The cross-correlation of the centre of room temperature and the external temperature has a correlation of 0.342 when no lag introduced. The peak correlation occurs for a lag of 2 hours in the centre of room temperature when the correlation becomes 0.408.

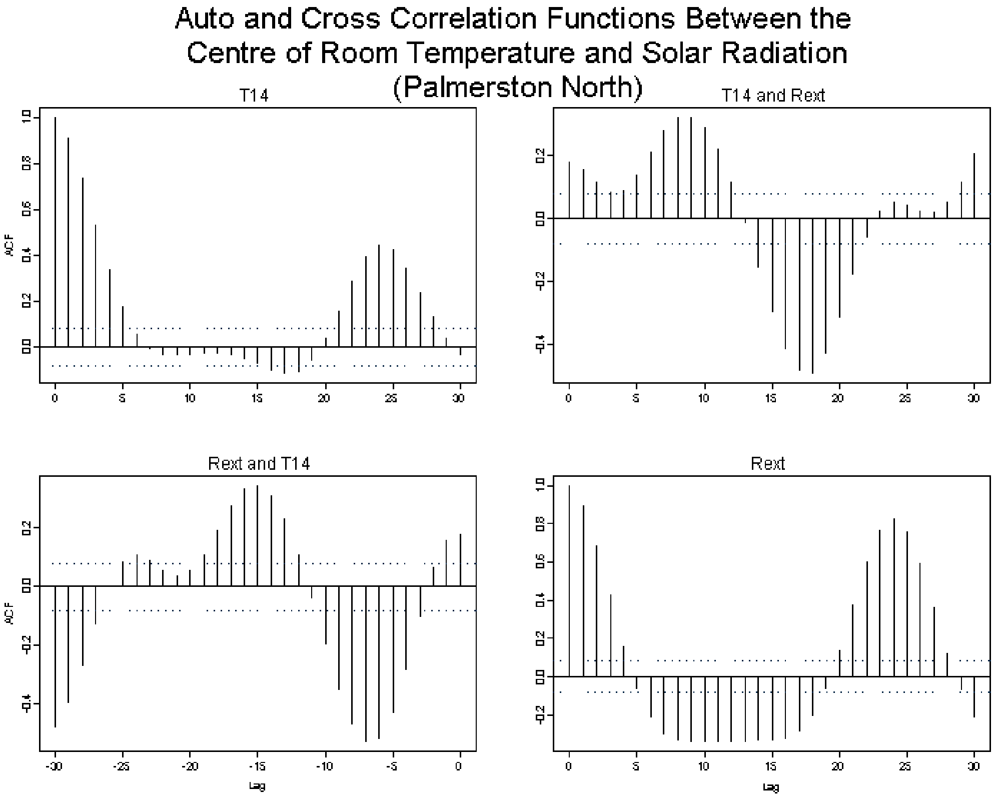


Figure 5.34 The auto-correlations and cross correlation of the hourly centre of room temperature (T14) and the hourly global horizontal solar radiation (Rext) for the Palmerston North data. Each lag step is one hour.

The cross-correlation of the centre of room temperature and the solar radiation has a local maximum when no time lag introduced between the functions however the value of the cross-correlation function of 0.178 is low. The highest absolute value for the cross-correlation is achieved with a lead of 7 hours for the centre of room temperature with a value of –0.527 however the large time lag and low correlation is suggestive of the peaks are co-incidental and not causal. Due to the difficulty in examining the solar radiation data, only auto correlations or cross correlations involving the indoor temperature and the external temperature were examined for Whitby.

For the measurements in Whitby during summer, an external Tinytag temperature logger was used to record the external temperature on-site. This logger was set to five minutes to match the intervals of the indoor temperature measurements. Figure 5.35 gives the auto-correlation and cross-correlation functions for the indoor temperature, T11 the highest sensor (1.9 m) on the array, and the external Tinytag temperature measurement. In this graph each lag is 5 minutes so that 288 lags is equal to one day.

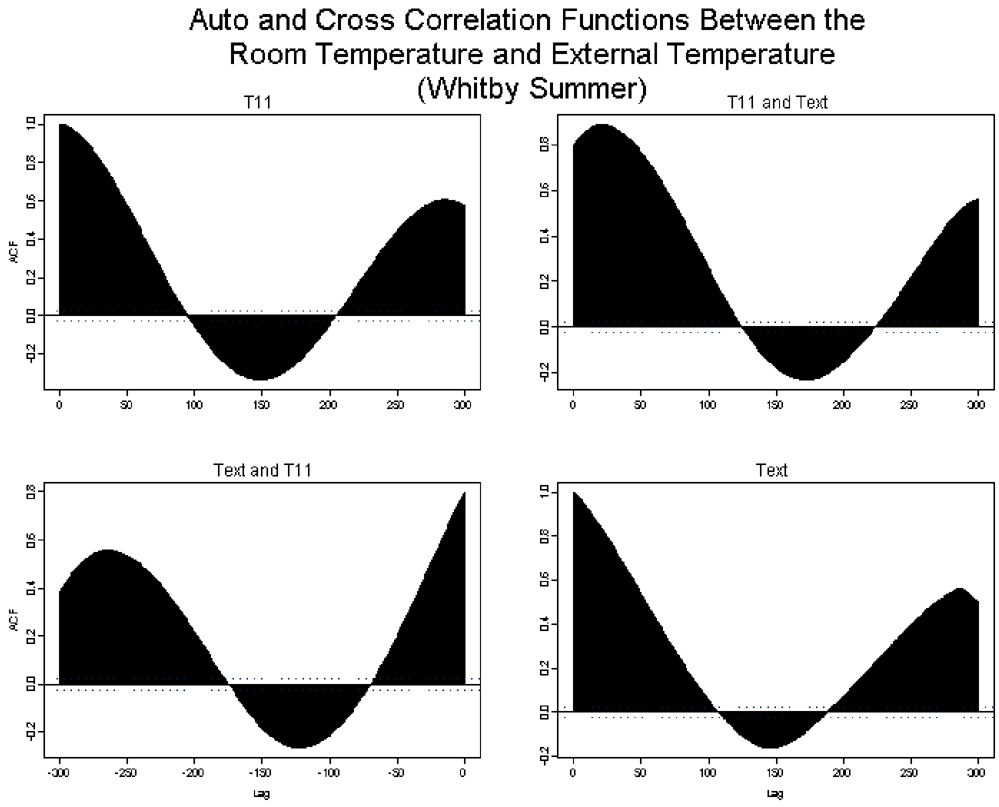


Figure 5.35 The auto-correlations and cross correlation of the five-minute top of array temperature (T11) and the five-minute external temperature (Text), recorded by an external Tinytag Temperature Logger for the summer Whitby data. Each lag step is five minutes. One day is equal to 288 lag steps.

For the Whitby (summer) data the auto-correlation function of the room temperature has a value of 0.606 when a 24-hour delay is introduced whereas the external Tinytag temperature has a value of 0.561. The cross-correlation function has a high maximum value of 0.890 for a time lag of 105 minutes in the indoor temperature.

For the Whitby (winter) data the external temperature was measured at NIWA agent 8567 and so only hourly data was considered. Figure 5.36 gives the autocorrelation and cross correlation functions of the room temperature, recorded by logger T103 at a height of 1.9 m, and the external temperature. The autocorrelation of the room temperature is 0.403 for a 24-hour lag whereas the external temperature has an autocorrelation of 0.441 for a 24-hour lag. The cross correlation of the room temperature and the external temperature has a flattish maximum value with the highest value occurring for a time lag in the room temperature of 5 hours when the cross-correlation becomes 0.623.

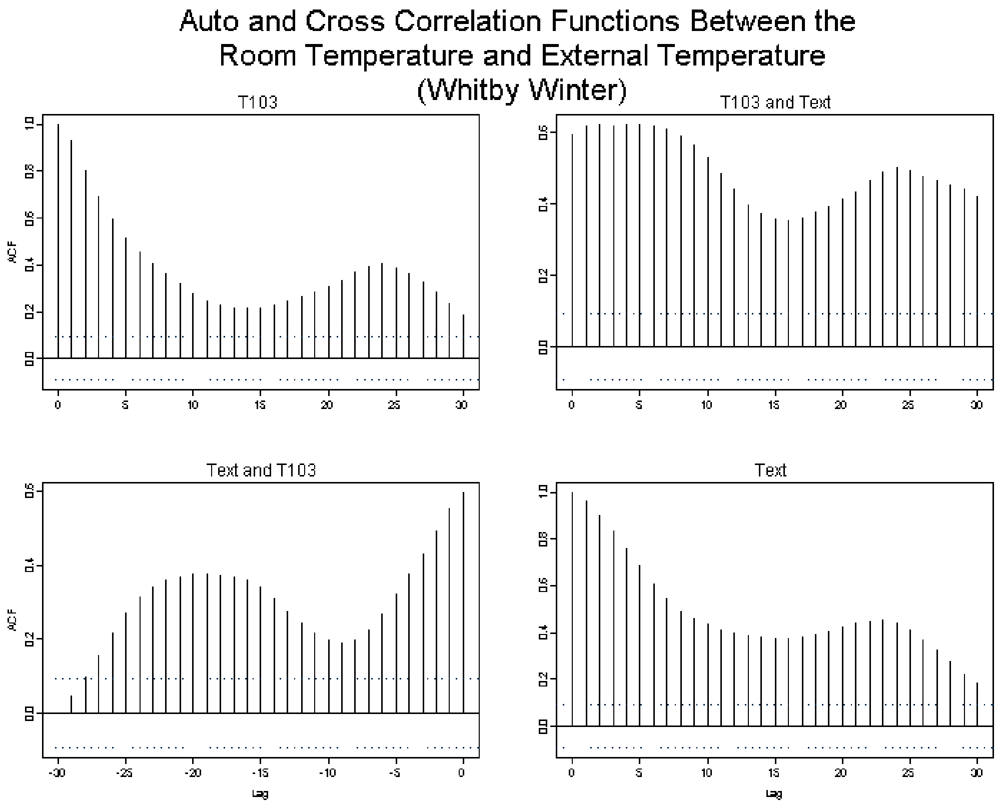


Figure 5.36 The auto-correlations and cross correlation of the hourly top of array temperature (T103) and the hourly external temperature (Text) for the winter Whitby data. Each lag step is one hour.

For the three datasets the indoor temperature is seen to lag behind the external temperature by between one-and-three- quarter hours (for the summer Whitby data) to five hours (for the winter Whitby data) though the winter data from Whitby has a flat peak ranging from two hours to six hours

5.8.1 Time Responses Between the Indoor Temperature Loggers

A number of temperature loggers were used throughout the living room of the Palmerston North house. The auto-correlations for these measurements look similar, as do the cross-correlations. The maximum cross-correlation between two temperatures will occur for a particular time lag between the two temperatures. Table 5.13 gives the time lag of the maximum cross-correlation for each pair of temperature loggers from the Palmerston North house. In Table 5.13 the logger at the top of the column leads the logger at the left of the row by the number of minutes shown (with a resolution of five minutes). In examining Table 5.13 loggers whose rows contain many large values are loggers whose temperatures lag behind the other loggers whereas loggers whose column contains many large values are loggers whose temperatures lead the other loggers.

Table 5.13 Time lag in minutes (resolution is 5 minutes) for each pair of temperature sensors within the room.

A non-zero entry indicates that the sensor at the top of the column leads the sensor at the left of the row by the number of minutes shown.

	T2	**T3**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T13**	**T14**	**T16**	**T17**	**T18**	**TT 26954**	**TT 26976**	**TT 46101**
T2											5	10	10		20		
T3											5	5	5		20		
T5											5	5	5		20		
T6											5	5	5		15		
T7	45	45	45	45		15	45	45	45	25	55	60	55	40	65	30	40
T8	30	30	30	30			30	30	30	5	35	40	40	25	50	15	25
T9		5	5	5				5	5		10	10	10		25		
T10											5	5	5		20		
T11											5	5	5		20		
T13	25	25	25	25			20	25	25		30	35	30	15	45	10	15
T14															15		
T16															10		
T17															15		
T18		5	5	5				5	5		10	10	10		25		
TT26954																	
TT26976	10	10	10	10			10	10	10		20	20	20	5	30		5
TT46101	10	5	5	5			5	10	5		10	15	20	5	25		

It can be seen that the sensors T7, T8 and T13 lag behind the other sensors whereas TT26954 seems to lead the other sensors. T7, T8 and T13 are all positioned along the southern internal wall of the living room with T7 and T8 being located within the wall unit. The Tinytag sensor TT26954 that leads all of the other sensors is located at the centre of the room upon the radiation shield of T14. This logger is perhaps more directly influenced by solar radiation than the other sensors and is less enclosed than the other sensors.

5.9 Closure

Eighteen temperature loggers were installed within the living room of a Palmerston North house with temperatures being recorded every five minutes. Included amongst these loggers was a vertical temperature array of four temperature loggers placed at heights of 0.4 m, 0.9 m, 1.4 m and

1.9 m. The sole space heating within the room was a flued gas heater whose output was monitored by placing a temperature sensor upon to tell when it is being operated. The hourly external temperature and global horizontal solar radiation were recorded by the automatic weather station at Palmerston North approximately 3 km away from the measured house.

From an exploratory analysis of the measured data, the height at which the temperature logger was placed appears to be an important determinant in the temperature reported by the logger.

To compare the vertical temperature distributions between houses, a house in Whitby had a vertical temperature array identical to the one used in Palmerston North installed and measurements were collected over two periods; one during summer and one during winter. During winter a woodburner was occasionally used to provide heating to the room.

The observed vertical temperature distributions were time dependent with the temperature level and curvature of the distribution being important dynamic parameters of the distributions. With the large amount of data collected, graphical analysis is useful. As three variables are of interest (temperature, time and height) graphing this data is not straightforward. A colour contour graph with the temperature as the suppressed z-value (the colour) was used and was seen to be effective in displaying the large amounts of data in a meaningful way.

Mathematical functions were fitted to the vertical temperature distributions. A low order function that fitted all three sets of data reasonably well was a modified quadratic function where the height of the maximum temperature (h) was fixed to a particular value for each of the sets of data used. The value for h for the different data sets varied and a better understanding of this variable would be useful. Fitting this modified quadratic function to the data allowed analysis of the temperature level and curvature of the vertical temperature distributions to be examined.

The curvature appears to be related to the heat input into the room. For the Palmerston North house the heat flows were large, vertical temperature gradients well defined and a clear relationship was seen between the use of the gas heater and curvature of the vertical temperature distribution. For the Whitby house the heat flows were smaller, the vertical temperature differences were smaller and the relationship between the calculated vertical temperature distribution curvature and the woodburner use was poor.

Temperatures from the same height from around the Palmerston North living room were also examined. Local temperature anomalies were observed and were possibly related to local heat flows due to nearby appliances or paths of low thermal resistance. As these anomalies are difficult to correct for, the initial placement of loggers should be carefully considered to minimise the variations observed in the temperature measurements.

Cross correlations between the indoor temperature and the outdoor temperatures were examined for the Palmerston North (120 minutes) and the summer (105 minutes) and winter (300 minutes) Whitby data. The time lags of the cross correlations of the all of the temperature loggers used in the Palmerston North house were examined. Three loggers were seen to lag the other loggers while one logger was seen to lead the other loggers. The reasons for these time lags are not clear.

Chapter 6

Temperatures Within All Saints Church

The temperatures within a non-residential building may depend on the climate, the building's thermal performance (NZS4243:1996), the heating system used within the building and how well the heat is distributed, the building's occupants as well as the use of the building (NZS4220:1982 and p 60, Baird, Donn and Pool 1983).

This chapter will report on temperature measurements within All Saints Church in Palmerston North. This building has a number of features distinct from those encountered in the residential buildings discussed in Chapter 5.

While the temperature measurements were being undertaken in All Saints Church, the Church was reviewing the heating system used within the building. This review was independent of the monitoring undertaken for this thesis. As part of this review, an electric radiant heater was trialled during the last two weeks of the temperature monitoring and attempts were made to measure the energy consumption of this heater. As heating is a prominent topic, section 6.3 will provide a brief discussion on heating options for All Saints Church.

6.1 All Saints Church, Palmerston North

The exterior of All Saints Church, Palmerston North, is shown in Figure 6.1. Churches (as examples of 'Places of Assembly'; ASHRAE 1995) frequently have a large volume with a high ceiling and are constructed from heavy-mass (such as brick or concrete) materials and have little or no insulation. The provision of adequate heating for such a design is a difficult task (Bowron, 2000) and consequently there is interest in the energy requirements and temperature patterns within such buildings (Harrison, Ackery and Wills 1952, Spielvogel and Rudin 1984, 1988a, 1988b).

All Saints Church was designed by Frederick de Jersey Clere, who designed many churches in the lower North Island at the beginning of the twentieth century. All Saints Church was built in 1914. The construction features of the Church include brick walls, a suspended timber floor and a metal skillon roof. A floor plan for All Saints Church is given in Figure 6.2 and a section view is shown in Figure 6.3.

A prototype microvolt logger (see Section 3.3.3) was used to take measurements of the indoor temperatures in All Saints Church between July 1998 and October 1998. Initially this prototype had only three thermocouple input channels but a later modification to the microvolt logger allowed for the use of a fourth thermocouple channel.

It was decided to locate the logger reasonably centrally within the knave of the church as shown in Figure 6.2. The logger was attached to the forward facing side of a column within the church at a height of 2.7 m. This logger was placed at this height to minimise the chances of people interfering with the logger and was placed on the forward facing side so the logger was not visible to people as they entered the church.

Figure 6.1 All Saints Church, Palmerston North.

It was also decided to measure the air temperature at a number of different heights. Thermocouples were placed on the column at heights of 3.8 m and 5.9 m. Another thermocouple was placed halfway along the adjacent pew, attached to the underside, at a height of 0.3 m. From the 29th August 1998, a fourth thermocouple was added at a height of 0.3 m on the column.

It was the intention to record indoor temperatures at a fifteen-minute interval and monthly visits were planned to collect the data from the logger. Unfortunately for two of the set-ups, the logger was incorrectly configured to record at a one-minute interval and as the data storage capacity of the logger, for one-minute datalogging is about five days, not all the data could be recorded, and consequently, data were lost. Over the entire logging period about half of the data were not recorded. This experience re-enforces the need to confirm that dataloggers are properly configured if they are left for an extended period of time.

The existing heating system employed in All Saints Church was a series of unflued reticulated natural gas heaters located throughout the church (shown as red squares in Figure 6.2).

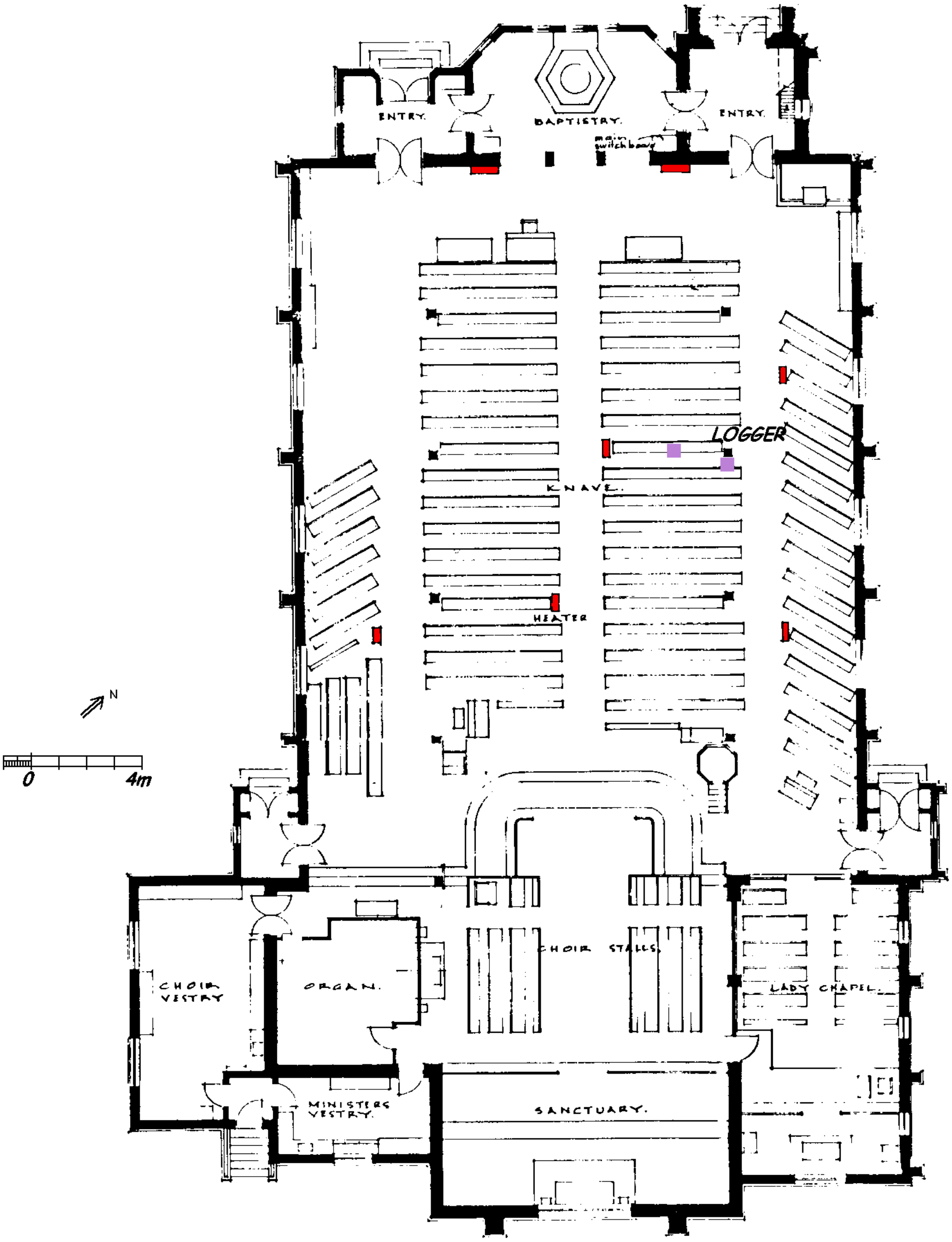


Figure 6.2 Plan view of All Saints Church (scale 1:250)

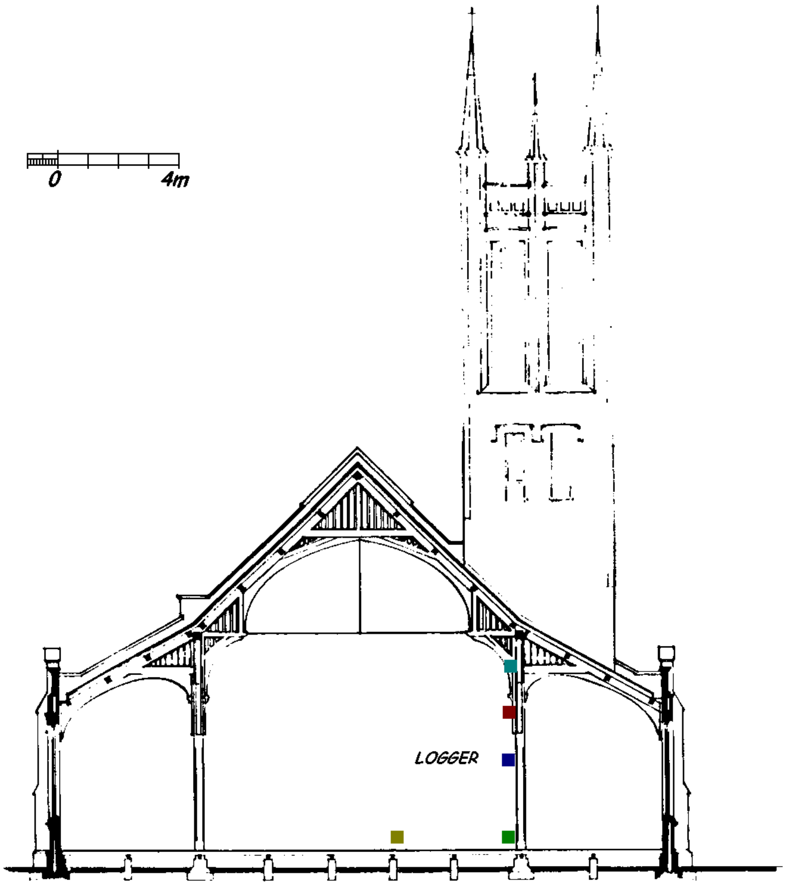


Figure 6.3 Section view of All Saints Church (scale 1:250)

Gas consumption to the church was not separately metered but meter readings of the site meter were taken. Meter readings over the measured period are shown in Table 6.1.

Table 6.1 Gas consumption for the site containing All Saints Church

Date	**Days**	**Gas Meter** ($\mathbf{m^3}$)	**Increment** ($\mathbf{m^3}$)	**Increment Per Day** ($\mathbf{m^3}$**/day**)
13/07/1998		42746.8		
2/10/1998	81	43807.2	1060.4	13.1
10/10/1998	8	43850.1	42.9	5.4
17/10/1998	7	43886.2	36.1	5.2

From the 2nd October 1998 until after the conclusion of the temperature monitoring on the 17th October 1998, the Church trialled the use of a 3200 W electric radiant heater. This radiant heater was suspended about 6 metres above the floor above the installed thermocouples.

In order to examine the linkage between the operation of the heater and the resulting temperatures within the building (by providing data as to when the heater was operating) it was intended to use a datalogger to record the energy consumption of the electric radiant heater.

The method used by HEEP for its total load energy measurements (Pollard 1999, Tries *et al.* 2000, Stoecklein *et al.* 2000) is to connect the load under investigation to an electronic Siemens S2AS watthour meter and record the digital pulsed output of the Siemens meter (one pulse for each accumulated one watthour of consumption). This output can be measured with a pulse logger (a datalogger to record the number of pulses per set time interval).

This method could not be used for All Saints Church as no pulse loggers were available at the time of monitoring (the BRANZ pulse loggers used for HEEP had yet to be developed). The Siemens meter however features a simple built-in datalogger that is capable of recording one week of half-hourly data. The recordings of this data logger are stored in volatile memory so that if there is an interruption of power to the Siemens meter then all the recorded readings will be lost. It was intended to make use of this built-in data datalogger capacity to measure the energy consumption of the electric radiant heater in All Saints Church.

The Siemens meter was initially housed in a plastic electrical connection box with a plug and three core flex cable feeding into the supply side of the Siemens meter and a three core flex and socket leading from the load side of the Siemens meter. The Siemens meter was provided to the electrician installing the heater for the Church and it was explained to him the need to have the Siemens meter constantly powered up. Unfortunately the heater was simply fitted with a plug with no switching between the heater and the Siemens meter installed. The only way to switch the heater on or off that did not lose the data from the Siemens meter was to connect or disconnect the plug of the heater from the socket attached to the Siemens meter leaving the Siemens meter permanently on. Instructions of how to turn on and off the heater were provided, however, as the 'live' switching had a tendency to spark, it is thought that the occupants chose to disregard these instructions and rather switched the heater on and off by operating the switch on the socket outlet the Siemens meter was connected (and powered) from. As the Siemens meter was powered down while the heater was not in operation, the data from the datalogger was lost so only the non-volatile meter totals from the LCD display on the front of the Siemens meter was recorded for each visit to All Saints Church. Table 6.2 provides records of these totals for each of the visits to All Saints Church while the radiant heater was being monitored.

Table 6.2 Electricity consumption of the trial electric radiant heater

Date	Days	Electric Heater (kWh)	Increment (kWh)	Increment Per Day (kWh/day)	Total Hours (hours)
2/10/1998		406.320			
10/10/1998	8	426.457	20.14	2.5	6.3
17/10/1998	7	435.693	9.24	1.3	2.9

6.2 Temperature Patterns

A time-series plot of the temperature measurements made in All Saints Church is shown in Figure 6.4, which also shows (in light blue) the hourly external air temperature for Palmerston North airport (NIWA Agent Number 3243) as reported in the NIWA climate database (Penney, 1997). The periods of interrupted data collection are clearly seen.

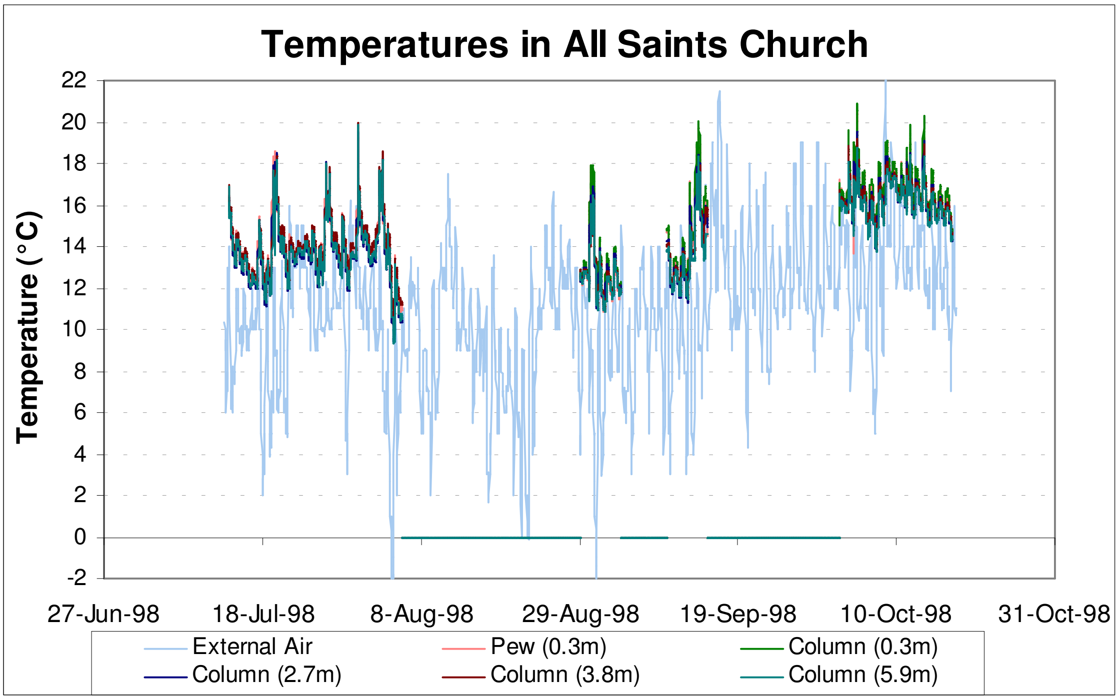


Figure 6.4 Time series of the temperatures in All Saints Church

Some basic statistics for all of the measured temperatures are given in Table 6.3 in the 'Pooled" column. The other column of Table 6.3 ('Instantaneous Range") gives some basic statistics of the difference between the highest temperature and the lowest temperature measured at any one instant in time. The mean instantaneous range is 0.70°C. For comparison, the mean of this instantaneous range for the Palmerston North house of Chapter 5 was 1.88°C. The temperatures in All Saints Church are comparatively similar, as the instantaneous range values appear small. Furthermore this comparison is strengthened as the measurements in All Saints Church were over at greater vertical separation (5.6 m as opposed to 1.5 m) and over a greater part of the season. The small variation in temperatures encountered in All Saints Church may be due to the known damping effect of the heavy mass (in this case, brick) construction on indoor temperatures, see Donn and Thomas (2001), Bellamy and MacKenzie (1999), Pollard and Stoecklein (1998a) and Isaacs and Donn (1994).

Table 6.3 Summary statistics of the temperature in All Saints Church (Pooled) and of the range of temperatures at any one instant in time (Instantaneous Range).

	Pooled	**Instantaneous Range**
Minimum:	9.31	0.06
1st Quartile:	13.12	0.45
Mean:	14.60	0.70
Median:	14.41	0.58
3rd Quartile:	16.16	0.81
Maximum:	20.89	3.03
Number of Measurements	41731	9184
Missing Values:	21078	4524
Variance:	3.64	0.17
Standard Deviation:	1.91	0.41
Skewness:	0.11	1.96

Figure 6.5 to Figure 6.8 give time series plots of the periods of consecutive data collection and Table 6.5 gives the basic statistics on the measurements from each of the sensors for each of these periods. Table 6.4 gives the dates of Sundays in the measured period. It is clear from the times series plots of Figure 6.5 to Figure 6.8 that the temperatures are elevated for Sundays.

Table 6.4 Dates of Sundays in the measured periods of the temperatures in All Saints Church

Period 1	**Period 2**	**Period 3**	**Period 4**
19 July 1998 26 July 1998 2 August 1998	30 August 1998	13 September 1998	4 October 1998 11 October 1998

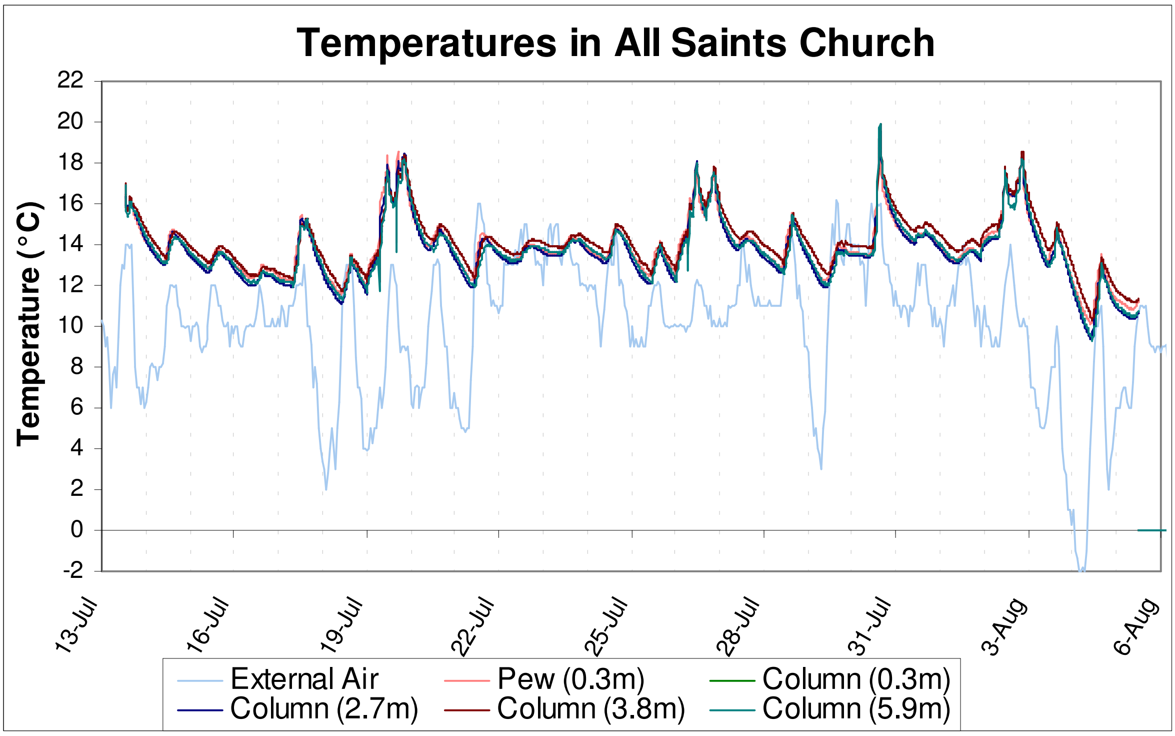


Figure 6.5 Temperatures in All Saints Church (Period 1)

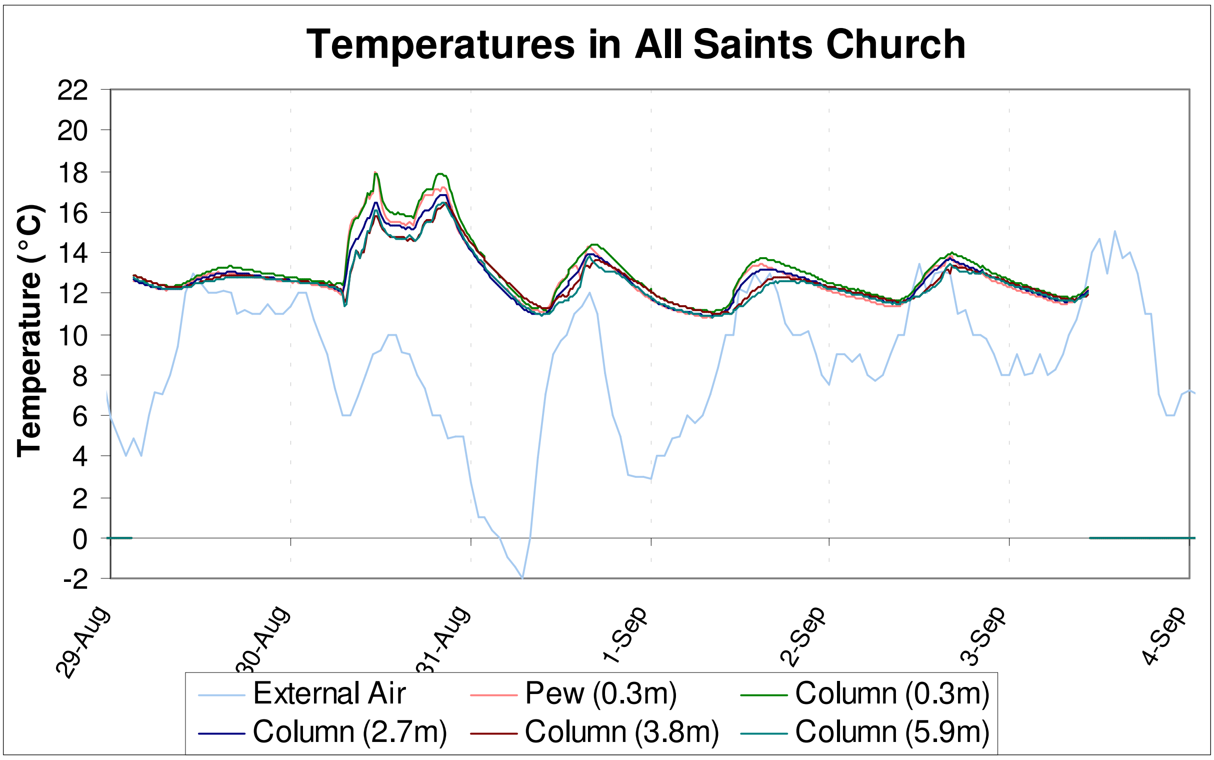


Figure 6.6 Temperatures in All Saints Church (Period 2)

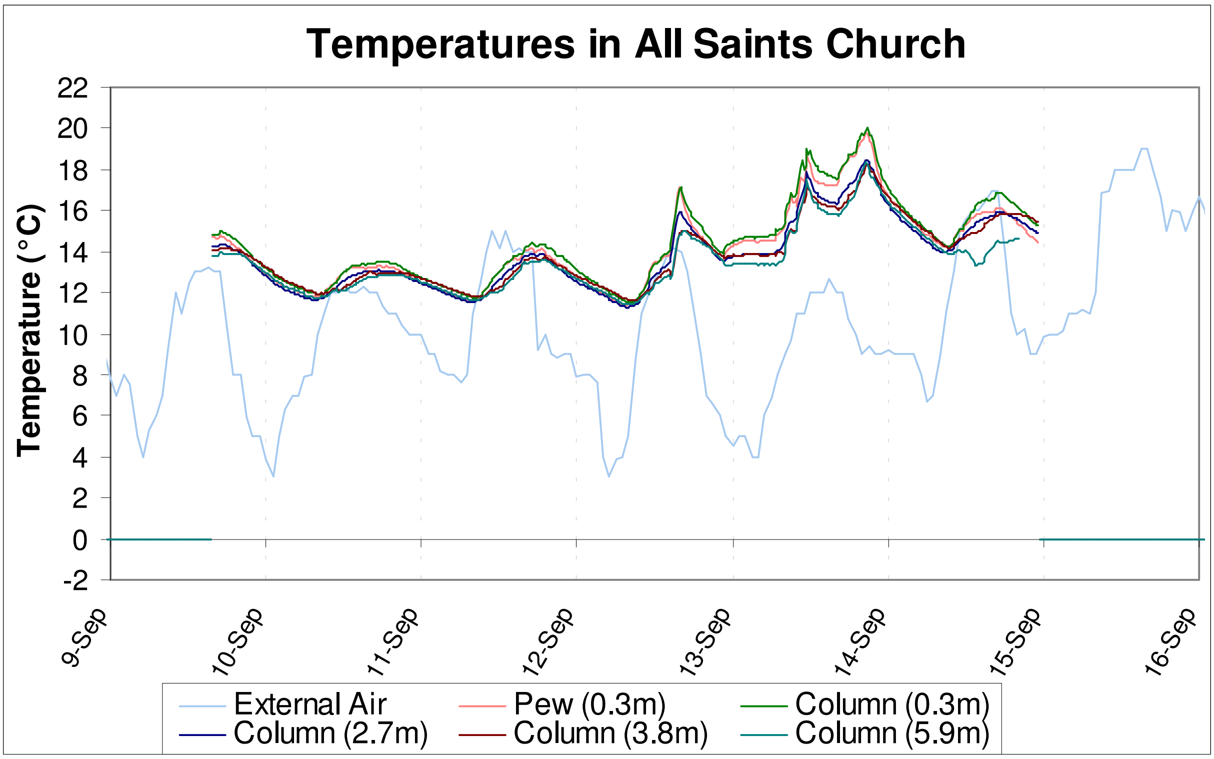


Figure 6.7 Temperatures in All Saints Church (Period 3)

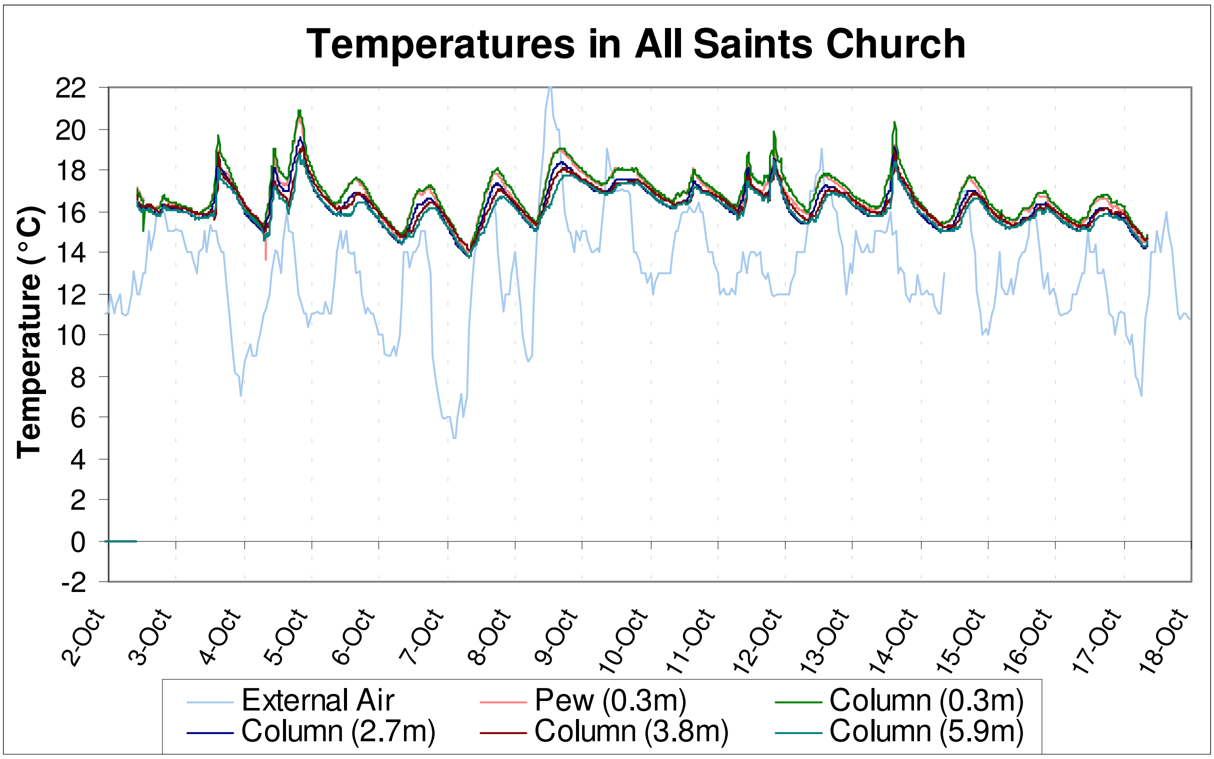


Figure 6.8 Temperatures in All Saints Church (Period 4)

Table 6.5 Basic statistics of the temperatures in All Saints Church for each consecutive data period

PERIOD 1

	Col (2.7 m)	Pew (0.3 m)	Col (3.8 m)	Col (5.9 m)
Minimum:	9.40	10.13	10.29	9.31
1st Quartile:	12.83	13.10	13.31	12.90
Mean:	13.65	13.84	14.11	13.70
Median:	13.52	13.71	13.98	13.60
3rd Quartile:	14.27	14.44	14.70	14.31
Maximum:	19.51	19.24	19.92	19.90
Number of Measurements:	2204	2204	2204	2204
Missing Values:	0	0	0	0
Variance:	2.30	1.89	1.88	2.13
Standard Deviation:	1.52	1.38	1.37	1.46
Skewness:	0.50	0.60	0.55	0.45

PERIOD 2

	Col (2.7 m)	Pew (0.3 m)	Col (3.8 m)	Col (5.9 m)	Col (0.3 m)
Minimum:	10.93	10.84	10.98	10.84	11.09
1st Quartile:	11.94	11.86	11.95	11.80	12.18
Mean:	12.76	12.82	12.68	12.55	13.11
Median:	12.55	12.55	12.51	12.40	12.78
3rd Quartile:	13.10	13.18	12.91	12.80	13.53
Maximum:	16.86	17.91	16.41	16.48	17.90
Number of Measurements:	511	511	511	511	511
Missing Values:	0	0	0	0	0
Variance:	1.65	2.11	1.24	1.36	2.21
Standard Deviation:	1.28	1.45	1.12	1.17	1.49
Skewness:	1.24	1.42	1.29	1.29	1.40

PERIOD 3

	Col (2.7 m)	Pew (0.3 m)	Col (3.8 m)	Col (5.9 m)	Col (0.3 m)
Minimum:	11.30	11.39	11.60	11.42	11.51
1st Quartile:	12.43	12.62	12.55	12.32	12.80
Mean:	13.83	14.16	13.86	13.53	14.42
Median:	13.72	13.90	13.67	13.36	14.18
3rd Quartile:	15.05	15.25	14.94	14.31	15.63
Maximum:	18.45	19.74	18.23	18.37	20.01
Number of Measurements:	511	511	511	511	511
Missing Values:	0	0	0	12	0
Variance:	2.92	3.67	2.51	2.34	3.97
Standard Deviation:	1.71	1.91	1.58	1.53	1.99
Skewness:	0.62	0.76	0.65	0.96	0.72

PERIOD 4

	Col (2.7 m)	Pew (0.3 m)	Col (3.8 m)	Col (5.9 m)	Col (0.3 m)
Minimum:	13.78	13.63	14.10	13.75	14.07
1st Quartile:	15.69	16.00	15.80	15.56	16.13
Mean:	16.29	16.64	16.33	16.09	16.82
Median:	16.20	16.58	16.25	16.03	16.73
3rd Quartile:	16.94	17.32	16.89	16.67	17.51
Maximum:	19.56	20.59	19.15	18.76	20.89
Number of Measurements:	1434	1434	1434	1434	1434
Missing Values:	0	6	0	0	0
Variance:	0.93	1.05	0.69	0.73	1.15
Standard Deviation:	0.96	1.03	0.83	0.85	1.07
Skewness:	0.24	0.30	0.24	0.15	0.45

Figure 6.9 gives a radial graph of the hourly temperature of the reference junction of the microvolt logger (on the column at a height of 2.7 m) for two days before, and two days after, Sunday, 26th July 1998. Each day is shown on the graph as a different colour. The top of the graph indicates midnight (00:00) with the day progressing in a clockwise direction. The plot starts on the Friday curve (dark green line) beside the 14°C label. The curve then continues clockwise is a roughly circular manner. At the top of the graph the curve changes colour to blue indicating Saturday and follows a slightly tighter circle indicating a slightly cooler day. For Sunday (red), heating is used and temperatures rise above 16°C for the morning and evening. The elevated temperatures that start Monday (purple) are reduced in an inwards spiral returning to an approximately circular shape for Tuesday (light blue). The decay in temperatures from Sunday night takes place over a number of hours returning to background levels by Monday afternoon. The slow rate at which this temperature reduces is again a result of the temperature damping effects of the heavy mass construction (brick) used in the Church.

The temperature profiles for each day of the week for the reference junction temperature of the microvolt logger are shown in Figure 6.10. The shape of the majority of curves in Figure 6.10 is similar however there is some distinction in the level of each profile. The shape of the Sunday profiles, contain more ‘sharp’ features indicating occupancy and heating. In Figure 6.11, normalised temperature profiles are constructed by plotting the difference of the temperature over the day from the temperature at the start (00:00) of for that day. From this shape information, the heating and occupancy events are more easily distinguished from the natural diurnal patterns of the building.

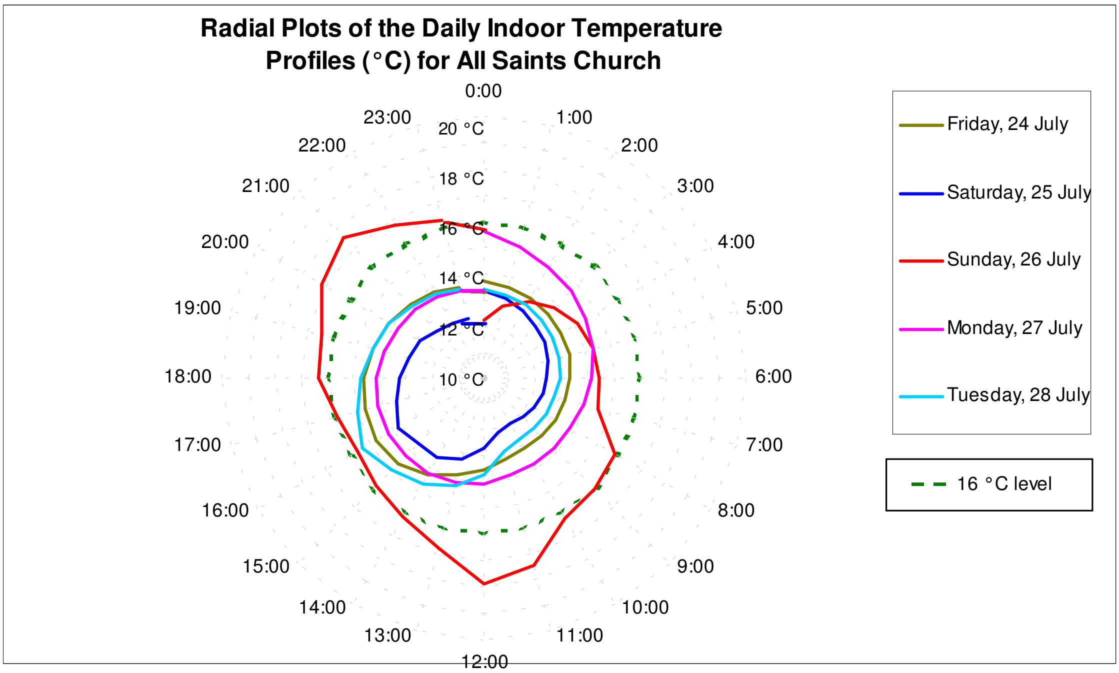


Figure 6.9 Radial graph of the indoor temperature in All Saints Church

For most days of the week, the final reading for the day is close to the temperature at the start of the day. The normalised temperature profiles (Figure 6.11) show that the temperature ranges for days of the week other than Sunday and Monday are centred on zero. The temperatures for Sunday end up warmer than at the start of the day, this is due to heating and occupancy over the day. Conversely the temperatures on Mondays end up cooler than the temperature at the start of the day. This is due to the Church still containing a significant amount of residual heat at 00:00 on Monday, which is then lost during the day.

The absolute temperature patterns within All Saints Church are relevant to the durability of building and its interior (particularly the organ) and are only of concern to occupants in terms of comfort and health when the building is being occupied. The profiles (Figure 6.10 and Figure 6.11) indicate regular Sunday occupancy, but also show other days where it is likely the church was being used. The Sunday profiles reveal that on the 30th August 1998, that the temperature at the microvolt logger was below 16°C for most of the day, only rising above 16°C at 11am for one hour and again at 6pm for 3½ hours. The other profile that drops below the 16°C threshold during the day is mid-winter day of 26th July 1998, where the temperature is below 16°C for three hours from 2:30pm. Table 6.6 gives the time on each of the monitored Sundays when the temperature first exceeds 16°C.

Table 6.6 The time the temperature in All Saints Church first exceeds 16°C on monitored Sundays

Date	**Time of first reading above 16°C**
19 July 1998	9:00
26 July 1998	9:30
2 August 1998	10:30
30 August 1998	11:00
13 September 1998	10:15
5 October 1998	9:00
11 October 1998	7:30

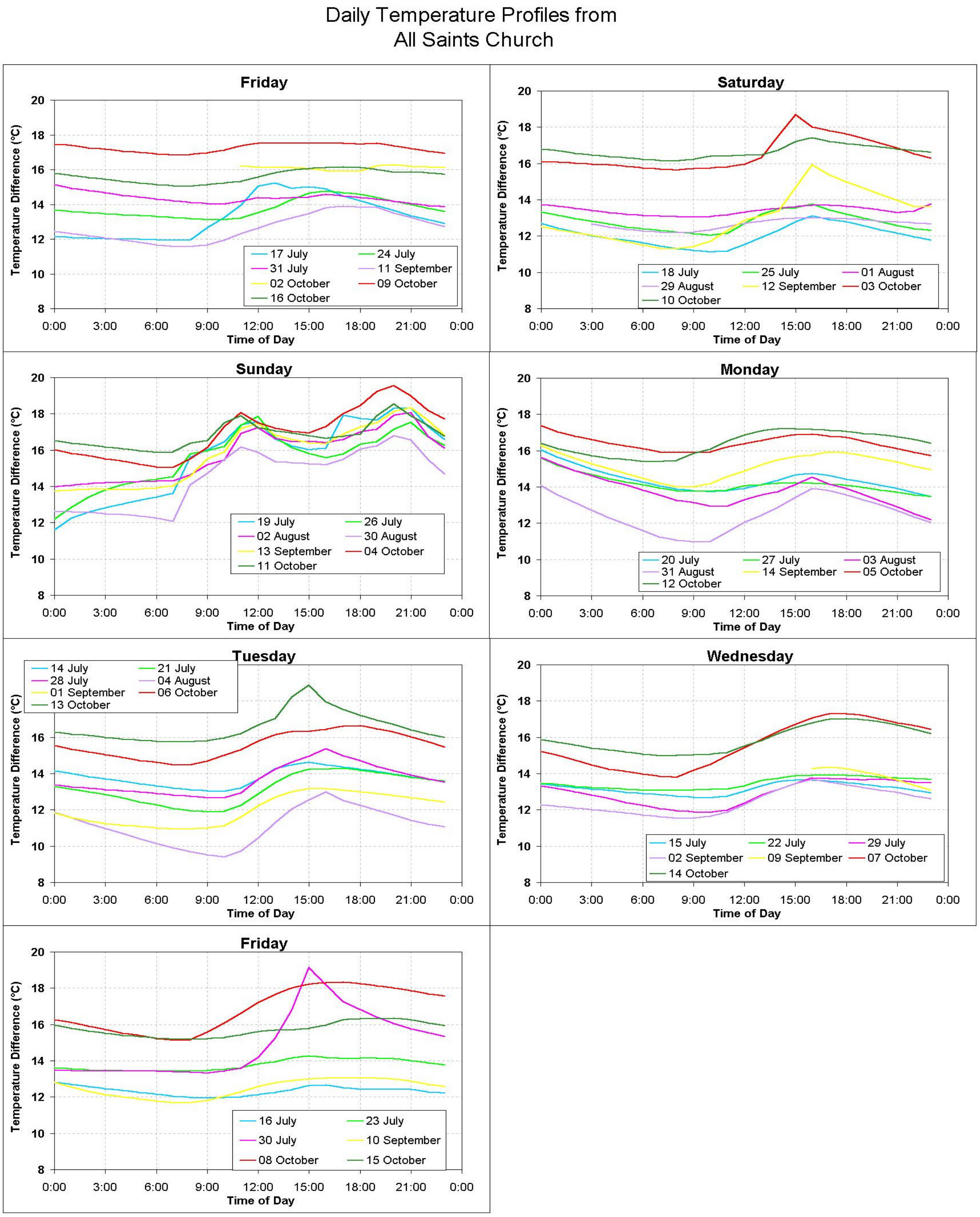


Figure 6.10 Daily temperature profiles for each day of the week

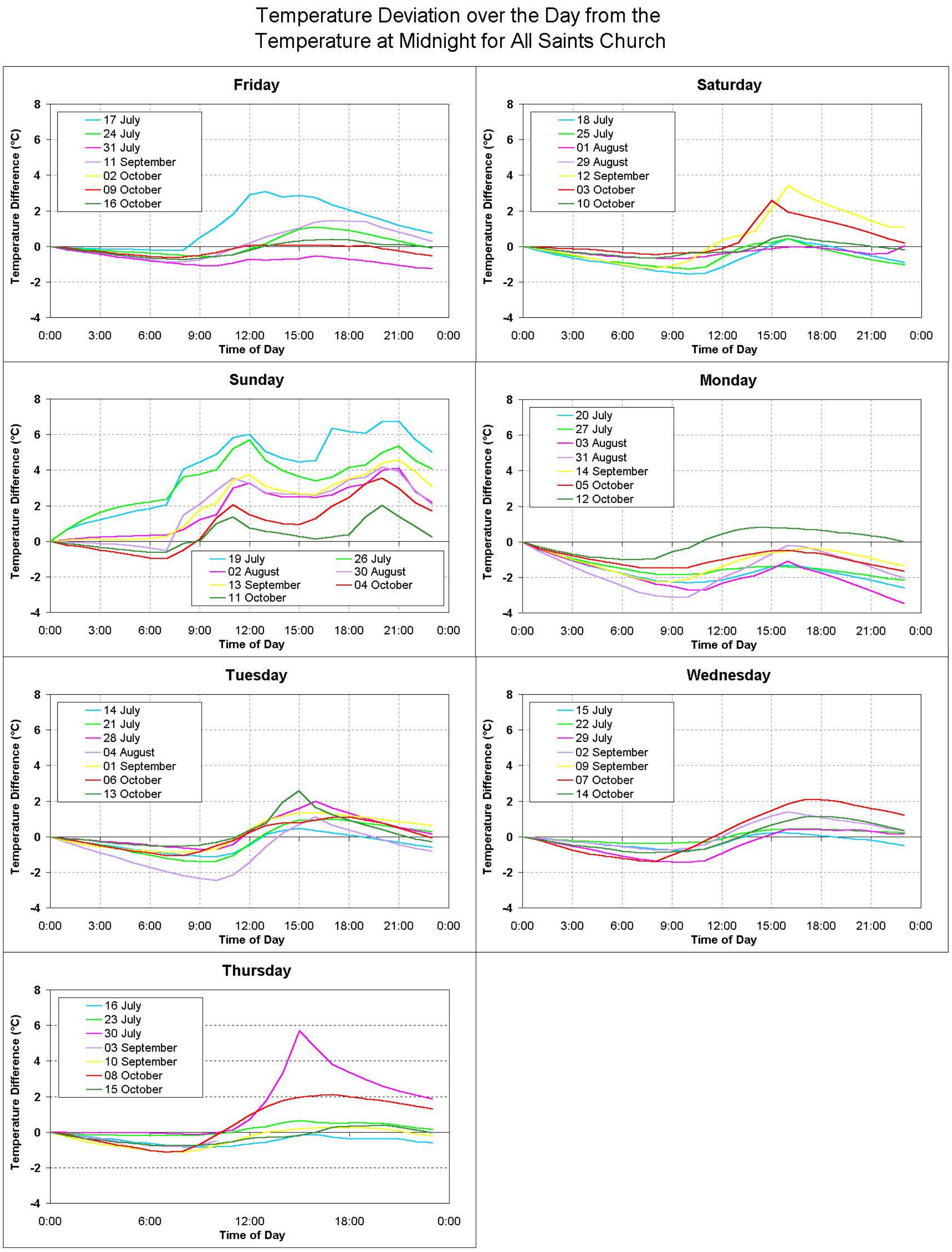


Figure 6.11 Normalised temperature profiles for each day of the week.

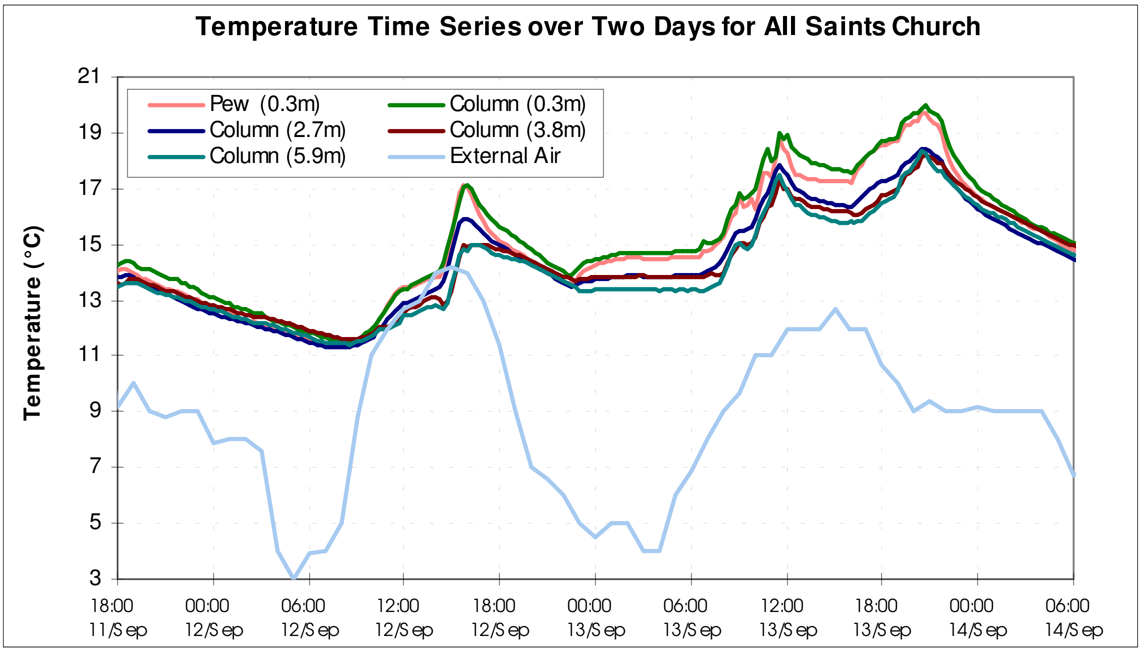


Figure 6.12 Temperature time-series over 60 hours. Note 13th September 1998 was a Sunday

Care must be taken when working with temperatures at a specific location, as the temperatures will differ from location to location. In particular, as the density of air changes with temperature, changes in the height of a measurement location may result in temperature changes. Figure 6.12 zooms in on one temperature time-series showing 60 hours of data (including Sunday, 13th September 1998). The temperature of the logger is shown as the 2.7 m column temperature (the dark blue line). The sensors underneath the pew (0.3 m, pink line) and at 0.3 m on the column (shown as the green line), which would generally be closer to the occupants of the church, show higher temperatures than those measured by the logger at 2.7 m.

The direction of the temperature change in going from the sensors at a height of 0.3 m to a height of 2.7 m is actually in the opposite direction as explained by the increased buoyancy of warmer air. Furthermore as the height is increased to 3.8 m and 5.9 m, the temperatures measured decrease even further, however the rate of the temperature reduction slows. A possible explanation for this decrease of temperature with height could be due to the slow diffusion of heat throughout the air in the church. As the heaters are located in the low occupied zone, they influence the low height temperatures more readily than the temperatures at a greater height.

In order to examine this disparity in temperatures from localised effects. A cross correlation analysis of the temperatures from period one and period four was undertaken. Due to the shortened length of period two and period three these were not included in the cross correlation analysis. Additionally hourly measurements of the outside temperature from the NIWA climate database was included. The resolution of each correlation with the outside temperature was one hour whereas for the resolution for the correlations between the indoor temperatures was fifteen minutes.

Table 6.7 gives the time in minutes the sensor at the top of the column leads the sensor at the left of the low according to where the peak in the cross correlation function between the sensors. The outside temperature is seen to lead the indoor temperatures by between three and five hours with the lower sensors responding faster than the higher sensors. For the indoor temperatures the higher sensors lag behind the lower sensors which is consistent with the suggestion that the temperatures within All Saints Church are largely localised.

Table 6.7 Duration of the time lag (in minutes) of the cross correlation between the temperatures from period 1 and period 4 of the measurements in All Saints Church.

PERIOD 1	Text	Pew (0.3 m)	Col (2.7 m)	Col (3.8 m)	Col (5.9 m)
Text					
Pew (0.3 m)	180				
Col (2.7 m)	180				
Col (3.8 m)	240	45	30		
Col (5.9 m)	240	30	15		

PERIOD 4	Text	Pew (0.3 m)	Col (0.3 m)	Col (2.7 m)	Col (3.8 m)	Col (5.9 m)
Text						
Pew (0.3 m)	180					
Col (0.3 m)	240					
Col (2.7 m)	240	15				
Col (3.8 m)	300	60	45	45		
Col (5.9 m)	300	60	45	45		

Consideration was given to more detailed modelling of the temperatures within All Saints Church. A building thermal simulation software program, such as SUNCODE (Wheeling and Palmiter, 1985), is able to model the thermal performance of a building by approximating the heat flow paths from each thermal zone of the building. A calibrated computer simulation (see section 3.4, DOE 2000a) makes adjustment to the simulated model until the simulated performance and measured performance are similar. The simulated model can then be applied to make predictions of the building's performance for other situations.

The inputs for these hourly simulation programs are hourly data of the heating and the occupancy of the building as well as the hourly climate the building experiences, such as air temperature and solar radiation. One of weather inputs required is the direct normal solar radiation. Unfortunately this measurement is difficult to make and is only available for a few select sites in New Zealand. Direct normal solar radiation data is not available for Palmerston North. Algorithms exist to approximate (van der Werff, Amor and Donn 1990, Amor, Donn and Rollo 1993) these values, however, these 'synthesised' values can not be directly compared with instantaneous measurements but instead require averaging over an extended period. With this issue making a comparison between the measurements made and a computer simulation difficult, a computer simulation of All Saints Church was not undertaken.

6.3 Effective Heating Strategies for All Saints Church

Before heating systems and strategies are put in place for a building, it is prudent to consider the extent to which the heating requirements can be minimised by considering; suitable insulation and thermal mass options, when people are present within the building, what volume of the building requires heating and what temperature level is required within this area.

All Saint Church presents a number of difficulties in minimising its heating requirements.

The infrequent use of the building is an important consideration as it is not the average temperature in the church that is important, but rather the temperature when the church is occupied (such as on Sundays). The heavy mass construction of All Saints Church means that it has a slow response to being heating or cooled down. To provide suitable temperatures when All Saints is occupied, sufficient heat needs to be supplied into the building with either a long preheat time or a large heating capacity.

It was seen in Section 6.2 that the temperatures within All Saints were localised. The highest temperatures were recorded at a low height which includes the heaters and seating. Insulation options would affect the heat flow some way from this localisation so are unlikely to be particularly useful in improving the temperatures or reducing the spacing heating within All Saints Church. The most practical insulation option is likely to be the installation of underfloor insulation as this is close to the higher localised temperatures.

The localisation of temperatures also discounts options concerned with the air distribution within All Saints Church. The use of ceiling fans during heating is given as an option for 'Places of Assembly' in ASHRAE (1995). The idea behind the use of these ceiling fans is to force the warm air than has risen back down to the level of the occupants. This clearly won't work for All Saints Church as the air temperatures above the occupants is cooler than the air temperature at the height of the occupants. The use of ceiling fans in All Saints Church would therefore only result in increasing the draught sensation and discomfort for the occupants.

The localisation of the temperature in All Saints Church is due in part to the large volume of air being heated. Different heating systems interact with the air within the room in different ways. Radiant heating systems create higher radiant temperatures within the room and consequently place an emphasis on heating objects (such as people) rather than heating the air. Convective heating systems, on the other hand, focus on the effective transfer of heat to the air within the room.

An advantage of radiant style heating is that the occupants are warmed directly by the long wave (infrared) radiation from the heater and may feel as comfortable as if they were in a room with a higher air temperature. By operating a room at a lower air temperature, heating energy savings may be made. Brown (1996) suggests that by using radiant heaters with a reduction in the air temperature of 3°C, heating energy savings of up to 65% can be made. However the temperature of the air should not be allowed to fall below 16°C as cold air can still affect the respiratory tract.

The use of radiant heaters places a greater importance on surfaces that are at a different temperature from their surrounds. For All Saints Church, the windows may need to be considered and options such as secondary glazing considered.

6.4 Closure

A selection of temperatures within All Saints Church has been measured. The collection of the measurements was problematic as the monitoring equipment was occasionally disconnected by the building's occupants. This is perhaps indicative of monitoring within a building being used by many people – as more people are involved the likelihood of user interaction with the equipment increases.

The influence of the heavy mass (brick) construction was seen to moderate the temperatures. Despite the range of heights of the temperature sensors and the monitoring extending over one quarter of one year, the variation in the temperatures was small.

The temperature patterns were strongly influenced by the occupants with the Sunday temperatures being distinct from the temperatures on other days.

The size of All Saints Church is large in comparison to the residential rooms previously examined and localised effects appear to be more important. The maximum temperature within the building occurs at a low height in the space where the heaters and seating are located.

Due to difficulties in heating the air, a radiant type heating system may be appropriate to achieve comfortable conditions within All Saints Church.

Chapter 7

Temperatures Throughout Residential Buildings

An outstanding problem is how to relate measurements gained in part of the building (within a particular room) to the rest of the temperatures throughout the building. Many building energy ratings schemes treat individual buildings as one zone and only work with one temperature (Stoecklein and Bassett 1998c). The Building Research Establishment's Domestic Energy Model (BREDEM, Anderson *et al.* 1985) considers buildings as composed of two zones; one being the living room with the rest of the house making up the other zone. The schedule for the heating of the living room is specified with the rest-of-house zone recorded as fully heated, partially heated or unheated.

This chapter will undertake an introductory examination of the measurements of the indoor temperatures throughout each house from the HEEP detailed temperature sample (comprising the nine Wanganui houses w11, w13, w16, w17, w18, w19, w20, w26 and w29).

7.1 Temperature Monitoring of the Detailed Temperature Sample

The temperature monitoring in the detailed temperature sample was undertaken during 1997. Five houses were measured in the first half of 1997 and four houses were measured in the second half of 1997. Table 7.1 gives the approximate periods of monitoring.

Table 7.1 Approximate period of monitoring and the restricted period for the detailed temperature sample.

House	Approximate Dates	Restricted Period Dates
w11, w13, w16, w17, w18.	19 Mar 97 – 20 Jul 97	22 Mar 97 – 20 Jul 97
w19, w20, w26, w29.	22 Jul 97 – 25 Jan 98	20 Jul 97 – 17 Nov 97

In order to provide a more uniform comparison of temperatures, the data for each house was restricted to a period of 121 days (about one-third of a year). This restricted period (also shown in Table 7.1) either concluded with 20 July 1997 (mid winter) for the first five houses or began with the 20 July 1997 for the second four houses. The height of each of the temperature loggers, and the room it was located in is shown in Figure 7.1.

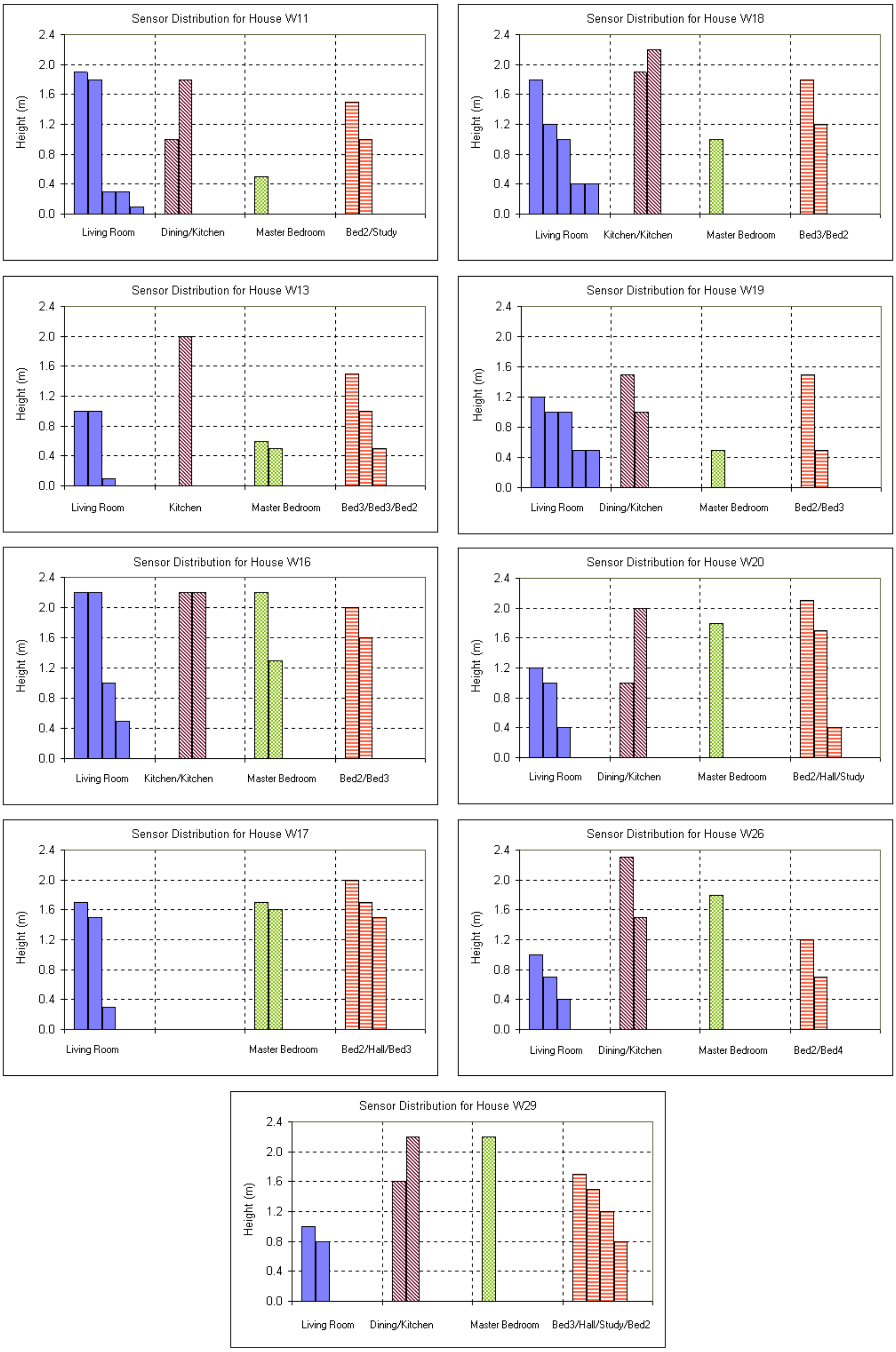


Figure 7.1 Heights of the temperature loggers in the detailed temperature sample.

At the time of monitoring (1997), experience with the placement of loggers was limited and the emphasis was to position a number of loggers at a variety of heights within the living room of a house and then to position the remaining loggers within the kitchen, dining area, master bedroom and other rooms (other bedrooms, hallway, study) of the house.

With the understanding of the importance of the vertical temperature differences (Chapter 5) different positions for the temperature loggers would have been used than those indicated in Figure 7.1. In particular, when more than one logger was positioned within a room, greater vertical separation of the loggers would have been attempted. For example for the two occasions when two temperature loggers were placed in the kitchen, both loggers were placed at a high location reducing the opportunity to examine the vertical temperature differences within the kitchens.

A number of temperature loggers were placed within the living room of each house. This data may be useful to examine the vertical temperature distribution within the living rooms of each house however the loggers are not at the same location within the room (they are both horizontally and vertically separately), not at evenly spaced heights and less than half of the houses had temperature logger placed within the upper half of the room (usually greater than 1.2 m). These issues may make establishing the vertical temperature distribution difficult.

It must be remembered that the positioning of the data loggers relative to other heat sources is still important. In was seen in Figure 5.31 that the temperature ‘TempTfrc’ (the leftmost logger in Figure 7.1) from w26 was influenced by the use of the TV.

Table 7.2 provides the average temperature from each logger over the restricted period (the layout for each house is similar to that used in Figure 7.1) and shows some inconsistencies in the vertical temperature distributions within the living rooms. W19 has an unusual profile which appears quite unpredictable. In addition to the TV influencing the highest temperature measurement point for W26, the lower two temperatures appear to be inconsistent and finally the second highest living room temperature from W18 appears to be about 0.7°C lower than expected.

Table 7.2 The average temperature recorded by each logger over a 121-day period.
The ordering of this table is the same as the order in Figure 7.1.

	Average Temperature (°C)													
House	Living Room					Dine	Kitchen		Master Bed		Other Rooms			
W11	17.8	17.9	16.8	17.0	15.8	16.0	17.8		15.6		16.9	15.6		
W13	14.8	14.6	14.4				15.6		13.9	13.3	14.6	14.0	13.0	
W16	16.1	16.1	15.2	15.0			15.3	15.6	16.1	15.3	15.2	13.8		
W17	17.5	17.7	16.6						17.3	16.8	18.1	17.6	16.7	
W18	15.9	14.5	15.1	14.7	14.8		16.8	16.4	15.4		15.2	14.5		
W19	15.3	15.3	16.3	15.8	15.7	17.4	17.0		14.2		14.7	14.9		
W20	17.4	17.3	16.3			16.0	16.5		16.0		15.0	16.1	14.0	
W26	17.0	15.9	16.5			17.6	16.8		14.4		13.5	13.7		
W29	15.0	14.3				14.6	15.6		14.4		13.5	13.2	13.2	14.1

The logger from bedroom 2 in W26 (13.5°C) had approximately 31% missing values. The other loggers had at most 4% missing values.

7.2 Properties of the Detailed Temperature Sample

The temperature data in Table 7.2 presented on its own provides only limited information. The extent to which the temperatures vary throughout a house depend on both physical properties (how compartmentalised the rooms are within the house, etc.) as well as behavioural properties (how much the occupants move around the house, how much the occupants like to have even temperatures throughout the house, etc.). The detailed temperature sample houses have also been surveyed using the HEEP survey and the following tables and graphs provide some indication of possible avenues for analysis using this surveyed data.

The size of a house and the level of insulation are factors in determining how effective the heating system used within the house is. Table 7.3 gives the size of the house in square metres and the decade each house was built (as the insulation standards took effect in 1978 houses built from the 1980's onward will have a minimum level of insulation). W17 was built in the 1980's so may be expected to have a reasonable level of insulation. In fact the temperatures throughout W17, as seen in Table 7.2, are, on average, warm in comparison to the other houses.

Table 7.3 Age and size of each monitored house.

House Number	Decade House Built	Estimated House Size (m^2)
W11	1970's	143
W13	1960's	117
W16	1950's	71
W17	1980's	82
W18	1950's	102
W19	1960's	102
W20	1970's	120
W26	1970's	*
W29	1950's	*

* House sizes for w26 and w29 had not calculated at time of writing

Information on the heating systems used within the houses was also surveyed. Figure 7.2 provides the number of heaters present within each house. It interesting to see that while W13 and W29 are at the opposite extremes of numbers of heaters owned within each house, from Table 7.2 they appear to have similar temperatures.

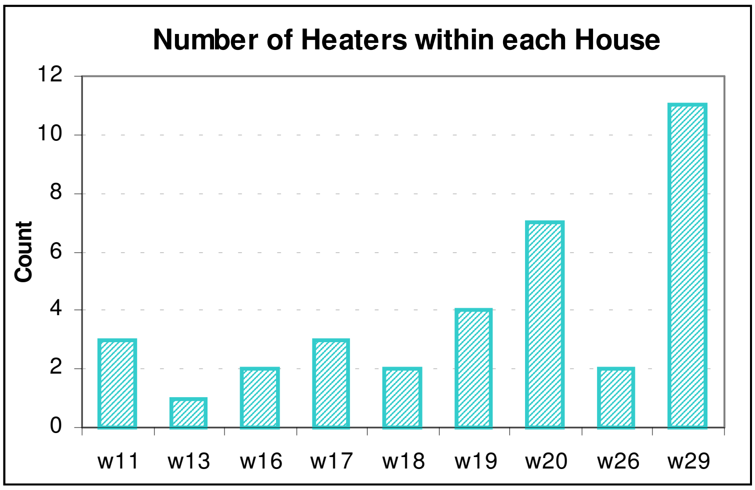


Figure 7.2 Number of heaters within each of the HEEP detailed temperature sample houses.

The total number of heaters within each house is not a measure of the overall heating capacity of the house. Portable electric heaters are only available up to 2.4 kW in capacity so a number of portable electric heaters are required to match the 12 – 20 kW output of a woodburner (Todd 2001). It could be noted that the single heating system in W13 is a woodburner.

The indoor temperature distributions may be influenced by demographic parameters such as the age distribution within the house. The elderly and the young require warmer indoor temperatures than the general population. It is interesting to see whether the age distributions (such as given for the detailed temperature sample in Table 7.4) and indoor temperatures can be related.

Table 7.4 Age distribution of the occupants of the households. (zeros have been suppressed)

House	**Total Occupants**	**Child Female**	**Child Male**	**Teen Female**	**Teen Male**	**Adult Female**	**Adult Male**	**Elderly Female**	**Elderly Male**
W11	3				1	1	1		
W13	2	1				1			
W16	2							1	1
W17	6	2	2			1	1		
W18	2							1	1
W19	2							1	1
W20	2					1			1
W26	6	2		1	1	1	1		
W29	2						1	1	

Household income is an important social factor and has been seen be an important influence on the indoor temperature within a house (Pollard and Stoecklein 1998b). Figure 7.3 shows that the incomes of the households in the detailed temperature sample are broad.

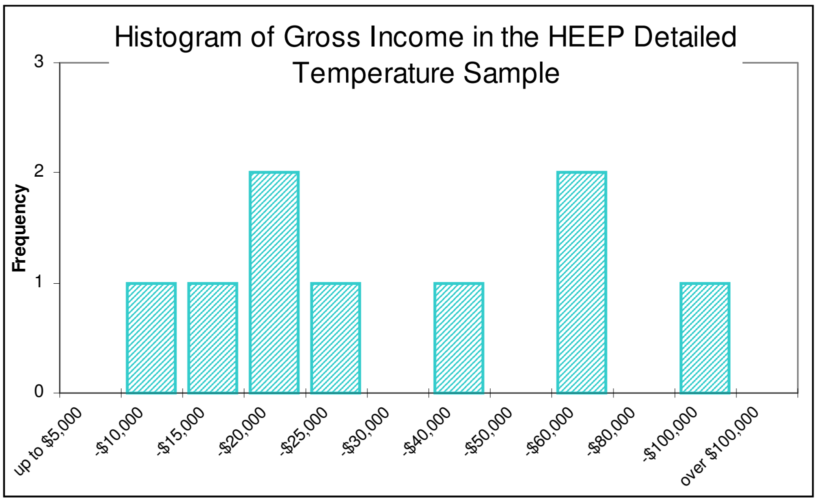


Figure 7.3 Histogram of the gross income of the households from the HEEP detailed temperature sample.

7.3 Principal Component Analysis

Principal component analysis (Mardia, Kent and Bibby 1979) is a data reduction technique that looks to summarise the information within a number of variables by creating a new set of orthogonal variables (the principal components) that are linear combinations of the old variables. The Principal components are ordered so that each additional principal component adds the maximum amount of information possible (the variance is minimised). Once the number of principal components matches the number of original variables then the data is fully described with no additional variation present in the data. Data reduction is achieved by represented the data by a fewer number of principal components than the number of original variables.

Principal component analysis has been used for building energy modelling by Olofsson (1997) and Reddy and Claridge (1994).

In order to assess how much redundant information is contained within the temperature measurements from houses in the detailed temperature sample, a principal component analysis was undertaken on the indoor temperature measurements for each house. Table 7.5 shows the proportion of the variation described by the first principal component for each of the sample houses.

Table 7.5 Variation of the indoor temperatures described by the first principal component of the temperatures from the detailed temperature sample.

	w11	**w13**	**w16**	**w17**	**w18**	**w19**	**w20**	**w26**	**w29**
Variation described by first principal component	81%	94%	86%	95%	96%	95%	93%	87%	96%

As can be seen the variation described by the first principal component is consistently high across the houses. For each case, the interpretation of the first principal component is the same, being the mean of all the indoor temperature measurements. The variation in the responses from each logger is consequently much larger than the variation between the loggers within each house. Any temperature logger within the house will quantify this effect.

With the first principal component being the dominant influence in the analysis the remaining principal components describe only a small amount of the variation within the data. All generally accepted methods to examine the number of principal components would result in only one principal component being taken to represent the data (Manly 1994).

In order to provide a better understanding of the temperature patterns within the house a transformed dataset was considered. This data consisted of time series information (at the 15 minute level) of the deviation of that logger from the mean of the all the temperature loggers at that time. This measure would give an indication of the variation of the temperatures within the house and would provide information on the number of loggers required to characterise the differences seen in the indoor temperatures. The cumulative variation described by each of the principal components of the deviations from the mean temperature (as described above) is summarised in Table 7.6 and a graphical display of the variation (scree plot) is shown in Figure 7.4.

Table 7.6 Cumulative variation described by the first five principal components of the principal component analysis of the difference from the mean temperature from the detailed temperature sample of nine houses.

Principal Component	**w11**	**w13**	**w16**	**w17**	**w18**	**w19**	**w20**	**w26**	**w29**
1	0.61	0.46	0.48	0.54	0.50	0.49	0.56	0.47	0.39
2	0.79	0.74	0.69	0.73	0.82	0.77	0.73	0.69	0.70
3	0.88	0.85	0.82	0.86	0.88	0.85	0.87	0.87	0.81
4	0.92	0.91	0.90	0.93	0.92	0.91	0.94	0.92	0.87
5	0.96	0.95	0.95	0.96	0.95	0.95	0.97	0.96	0.92

Scree elbow (estimated)	2	3	2	2	3	3	2	3	3

While it appears that the scree plots suggest that some of the houses need only two points, when the cumulative variation described by the principal components is considered it is seen that houses with an elbow at the second principal component describe less variation with the two principal components than the other houses that appear to need three principal components (from the elbow). The conclusion is that three principal components are required to represent the variation in the indoor temperature from the mean indoor temperature within the house.

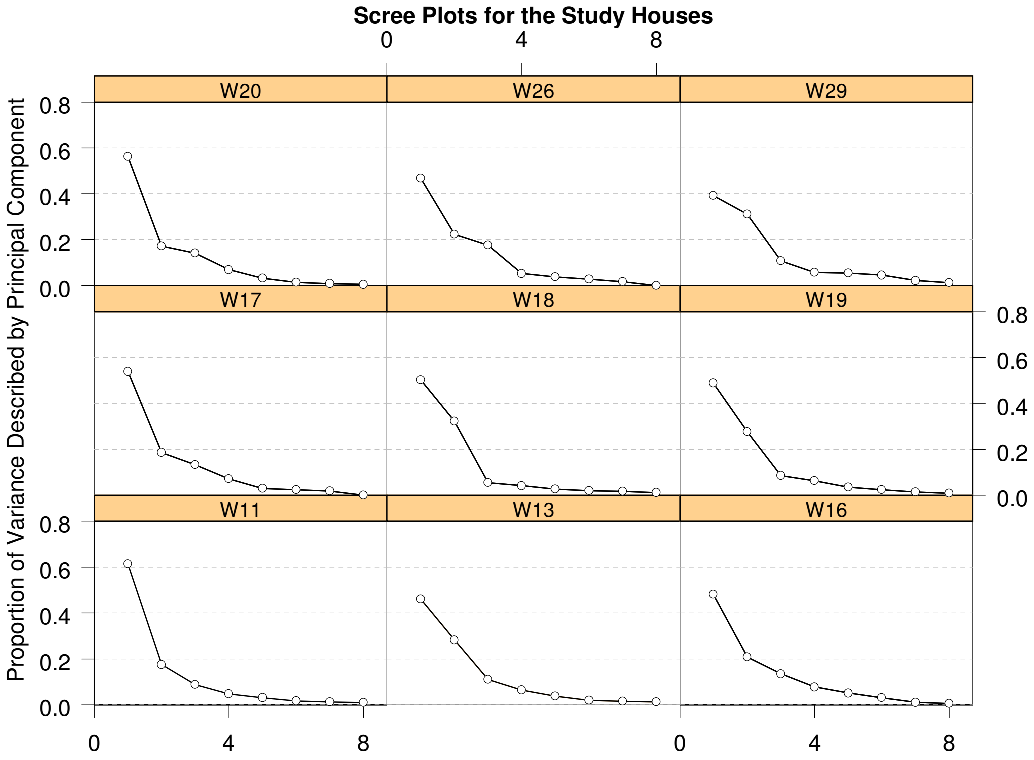


Figure 7.4 Scree plots of the principal component analysis of the difference from the mean temperature from the detailed temperature sample of nine houses.

The structures of the first three principal components can be assessed across of the houses to determine if there are specific issues concerning the placements of loggers within a house. Appendix E gives plots of the components of the first three principal components of the differences from the mean temperature from each of the detailed temperature sample houses. The structures of the principal components appears to relate to the differences in temperature between the living room and the master bedroom (or other rooms away from the living room), the loggers placed at high height to those loggers placed low down, as well as the temperature differences between the living room and the kitchen/dining room.

In placing three temperature loggers within a house an emphasis may be to place two loggers in the living room (to examine vertical temperature differences) and one logger in the master bedroom (to examine the contrast between the living room and the rest of the house).

The suitability of the temperature differences from the mean temperature as a transformed dataset has not yet been established. As there are a number of measurements of the living room, the living room is over represented in the mean temperature for the house. The external temperature may be used in place of the mean temperature however this introduces an offset into the data and again the first principal component becomes a measure of this average effect. Transformations such as taking a ratio of the absolute temperatures (as was done in Chapter 5 to determine when the gas heater was on) may be more effective than the temperature differences.

7.4 Closure

In looking to describe the indoor temperatures throughout a house, the temperatures within each room have to be well described. The vertical temperature distribution was earlier seen (Chapter 5) to be an important factor in the living room temperatures from one of the two houses examined. More information on the vertical temperature distributions in other rooms may be beneficial to understanding the temperature distribution throughout a house.

The wider the temperatures are measured within a house, the more the social factors become important determinants in the indoor temperatures. A number of physical and social factors were examined for the detailed temperature sample in Section 7.2 and comparison made to the measured indoor temperatures.

The temperatures throughout a house are, however, highly correlated and a principal component analysis of the raw temperatures will give one main principle component that has a simple interpretation as the average of all of the temperature measurements. In order to make better use of principal component analysis the dataset needs to be first suitably transformed so the data better represents differences throughout the house.

Chapter 8

Conclusions

Small, self-contained temperature loggers are a practical way to collect indoor temperatures from buildings. A good level of accuracy is readily achievable for such loggers and uncertainties of better than 0.2°C have been measured for the BRANZ Temperature Logger and the BRANZ Microvolt Logger.

For this thesis, the temperatures measured within a number of buildings have been used. As programmes such as the Household Energy End-use Project (HEEP) continue, more information on the indoor temperatures in New Zealand buildings will be collected.

8.1 What Measured Indoor Temperatures Reveal

The occupants play a major role in determining the indoor temperatures within a building. How frequently the building is heated can be identified from the indoor temperature data. Daily patterns were observed within houses and weekly patterns were seen for All Saints Church. The comfort expectations of the occupants are also an important factor that can be examined from the comparison of the temperature measurements from a number of different buildings. Occupants also interact with the monitoring process; when an electrical space heater being monitored in All Saints Church was switched off, the equipment used to monitor its energy consumption was also switched off losing most of the data collected on the usage of the heater.

The response of the indoor temperature within a building to changes in the outside conditions (air temperature, solar radiation) and operation of heaters is not an immediate effect and depends on the design and construction of the building. The influence of the heavy mass (brick) construction within All Saints Church was seen to moderate the indoor temperatures and despite the range of heights of the temperature sensors and the monitoring extending over one quarter of one year, the variation in the temperatures within All Saints Church was small. In another example, the large area of windows in the design of W20 (see Section 4.3) meant that the response of the indoor temperatures in W20 to solar radiation was rapid and large but that the building also cooled down quickly.

The size of the heat flows into a room determines whether strong temperature variations are observed. One identifiable temperature variation within small rooms is the presence of vertical temperature gradients. It was seen in 0 that the graphical display of the temperature-height-time information in a colour contour plot permits the large amount data on the vertical temperature distributions to be examined. Properties of the vertical temperature distributions can be related to parameters such as the heat flow into the room if the vertical temperature distribution is well defined.

8.2 Placement of the Indoor Temperature Loggers

From the measurement of the indoor temperatures within a number of buildings many issues concerning the placement of the temperature loggers were encountered. The placement of temperature loggers can be localised as follows;

- Location within the building (which room the measurements are located in)
- Location within the room
- Location relative to sources of heat

these issues will be summarised in the following three sections.

8.2.1 Location Within the Building

Central heating systems are rare in New Zealand houses and consequently whole house heating is not frequently encountered. Temperatures throughout a house depend on the extent to which the occupants desire to have separate rooms heated. From initial work, there appears to be a contrast between the living room and the main bedroom, perhaps because these rooms are frequently located in different areas of the house or heated differently.

Consequently these are the rooms to be targeted in measuring the indoor temperatures within a house.

Within non-residential buildings the functional use of the building is an important issue to be considered and need to be treated on a case-by-case basis.

8.2.2 Location Within the Room

Within a small room the temperature distribution is subject to localised perturbations but is essentially horizontally homogeneous. There are however systematic variations in the vertical temperature distributions due to the presence of heating. Within the main heated area, loggers should be placed in suitable locations that also have a maximal vertical separation between them to give an indication of the impact of heating within this room.

Within larger rooms elevated temperatures are observed close to where the heating is occurring. Vertical temperature difference becomes less pronounced and the general trend of increased temperature with increased height may not be observed.

8.2.3 Location Relative to Sources of Heat

Within a room there are strong localised effects that can give rise to anomalous temperature readings for individual temperature loggers relative to the expected room temperature at that particular height.

The radiative heat to a temperature logger should be minimised by not placing the logger in the direct path of strong radiant sources. Radiant sources comprise not only of direct solar radiation through windows but also electrical lights (at least 1 m away from bulbs) and high temperature radiant heaters (electric radiant heaters, radiant gas heaters, portable LPG heaters, open fires).

Conductive heat flows should be reduced by minimising the contact of the logger with surfaces at different temperatures from the air temperature. Preferably as much air as possible should surround the logger. Where the logger needs to be placed in contact with a surface at a different temperature to the surroundings - an insulation layer (such as 10 mm expanded polystyrene) should be used to separate the logger from the surface.

To minimise convective heat flows the loggers should not be placed in a position where air movement is higher than for the majority of the room. Draughts may occur near to the ceiling or floor so the so the loggers should be placed no closer than 200 mm from these surfaces. Loggers should not be placed over operable windows or doorways. Where active ventilation systems are present, the temperature loggers should not be placed close to the inlet or outlets.

The loggers should not be nearby to any heat sources (heaters, electrical appliances, TVs, lights, refrigerators, domestic hot water cylinders, etc.) or heat sinks (windows, adjoining cold rooms, etc). Adjoining rooms should be examined, for strong heat sources (or sinks) near to the shared wall, in particular refrigerators and domestic hot water cylinders should be avoided.

8.3 Areas for Future Investigation

There are a number of areas covered by this thesis that would benefit from further analysis. The analysis of the temperatures throughout a house was introduced in Chapter 7 and would benefit from a more detailed examination of the height variation of the temperature measurements throughout the house was well as a better understanding of the degree to which only part of the house is heated.

The vertical temperature distributions were measured in two houses and provided some contrasting results. Additional detailed measurements of the vertical temperature distribution could be made and further examination made on such issues as the change of the height of the temperature maximum for different houses and different seasons.

References

References with the author and year listed in red are available in electronic format (usually in PDF format) and are included on the CD with this thesis.

Amor, R., Donn, M. and Rollo, J. 1993. *"New Z ealand Weather Data for DOE2 and SUNCODE"*, Report from the Centre for Building Performance Research, Victoria University, Wellington.

Anderson, B. R., Clark, A. J., Baldwin, R. and Milbank, N. O. 1985. *"BREDEM: The BRE Domestic Energy Model",* Information Paper IP16/85, Building Research Establishment (BRE), Garston, England.

ASHRAE 1987. *"ASHRAE 41.1–1996 Standard Method for Temperature Measurement"* ASHRAE Standard ANSI/ASHRAE 41.1-1996, Atlanta, USA.

ASHRAE 1992. *"ASHRAE 55-1992 Thermal Environmental Conditions for Human Occupancy"*, ASHRAE Standard ANSI/ASHRAE 55-1992, Atlanta, USA.

ASHRAE 1995. "*ASHRAE Handbook: HVAC Applications",* ASHRAE, Atlanta, USA.

ASHRAE 1997. *"ASHRAE Handbook: Fundamentals"*, ASHRAE, Atlanta, USA.

Auliciems, A. and Szokolay, S. 1997 *"Thermal Comfort"*, PLEA Notes 3, Passive and Low Energy Architecture International and Department of Architecture - University of Queensland, Brisbane, Australia.

Baird, G., Donn, M. R. and Pool, F. 1983. *"Energy Demand in the Wellington Central Business District",* NZERDC Report 77, Auckland.

Balcomb, J. D. 1983. *'Heat Storage and Distribution Inside Passive Solar Houses",* Report LS-9694-MS, Los Alamos National Laboratory, Department of Energy, Los Alamos, USA.

Bartels, R. 1998. *'Metering and Conditional Demand Analysis: How to Get the Mo st for the Least",* Presentation at the Non-Intrusive and Other End-Use Metering Systems Workshop, 23-24 September 1998, Amsterdam, The Netherlands.

Bassett, M. R., Amitrano, L. and Mayson, M. 1996. "*Energy Efficiency of Houses in Wanganui Determined From the HERO Programme*", Proceedings of the 1996 IPENZ Conference, Dunedin.

Bell, M., Lowe, R. and Roberts, P. 1996. *'Energy Efficiency in Housing"* , Ashgate Publishing, Aldershot, England.

Bellamy, L. and MacKenzie, D. 1999. *'Thermal Performance of Concrete versus Timber-Framed Walls in Side-by-Side Test Buildings: Results from Base-Case and Ventilation Trials",* Proceedings of the 37th Australian and New Zealand Solar Energy Society Conference, 1-4 December 1999, Deakin University, Australia.

Bishop S., Camilleri, M., Dickinson, S., Isaacs, N., Pollard, A., Stoecklein, A., Jowett, J., Ryan, G., Sanders, I., Fitzgerald, G., James, B. and Pool, F. 1998. *'Energy Use in New Zealand Households: Report on the Household Energy End Use Project (HEEP), Year 2",* Energy Efficiency and Conservation Authority, Wellington.

Boardman, B. 1991. *'Fuel Poverty: From Cold Homes to Affordable Warmth",* Belhaven Press, London.

Bowers, S. 1998 *'Review of Evidence for Housing -related Interventions to Reduce Health Inequalities",* Background paper prepared for the Programme on social, cultural and economic determinants of health, National Health Committee, Wellington.

Bowron, G. and Richardson, P. 2000. *'Guidelines for Altering Historic Churches* ", Heritage Guidelines 9, New Zealand Historic Places Trust, Wellington.

BRANZ 1993. *'HERO Set to Save Homeowners from Energy Wastage",* BUILD, August 1993.

Breuer, D. R. 1988. *'Energy and Comfort Performance Monitoring of Passive Solar Energy Efficient New Zealand Residences"*, New Zealand Energy Research and Development Committee Report No. 171, Wellington.

Brown, R. G. 1996. *'Radiant Heating"* , Building Services Research and Information Association Application Guide AG3/96, Bracknell, England.

Camilleri, M., Isaacs, N., Pollard, A., Stoecklein, A., Tries, J., Jowett, J., Fitzgerald, G., Jamieson, T. and Pool, F. 1999. "*Energy Use In New Zealand Households: Report on Year 3 of the Household Energy End Use Project (HEEP)",* Energy Efficiency and Conservation Authority, Wellington.

Camilleri, M., Isaacs, N., Pollard A., Stoecklein A., Tries, J., Jamieson, T., Pool, F., and Rossouw, P. 2000. "*Energy Use in New Zealand Households – Report on Aspects of Year Four of the Household Energy End-Use Project (HEEP)*", BRANZ Study Report 98, Judgeford.

Camilleri, M. 2000. *'Implications of Climate Change for the Construction Sector: Houses.",* BRANZ Study Report 94, Judgeford.

Chastain, J. P. and Colliver, D. G. 1989. *'Influence of Temperature Stratification on Pressure Differences Resulting from the Infiltration Stack Effect"*, ASHRAE Transactions, Vol. 95, Part 1, pp. 256-268.

Chen, Q. and Jiang, Z. 1992. *'Significant Questions in Predicting Room Air Motion"* , ASHRAE Transactions, Vol. 98, Part 1, pp. 929-939.

Commerce, Ministry of, 1999. *"Climate Change What You Should Know"*, Ministry of Commerce, Wellington.

Cox-Smith, I. 2001. *'Whole -Wall R-Values",* Proceedings of the 2001 CIB World Building Congress, Wellington.

Cunningham, M. J. 1996. *'Controlling Dust Mites Psychrometrically – a Review for Building Scientists and Engineers"*, Indoor Air, **6**, pp. 249-258.

Dallas Semiconductor 1998. Data sheet for Dallas DS1624S (downloaded from http://www.dalsemi.com/).

De Dear, R. Brager, G. and Cooper, D. 1997. *'Developing an A daptive Model of Thermal Comfort and Preference"*, ASHRAE Report RP-884, Georgia, USA.

Donn, M. and Thomas, G. 2001. *"Designing Comfortable Homes: Guidelines on the Use of Glass, Mass and Insulation for Energy Efficiency"* Cement and Concrete Association of New Zealand, Wellington.

EECA 2000. *"The Dynamics of Energy Efficiency Trends in New Zealand – A Compendium of Energy End-Use Analysis and Statistics"*, Report by the Energy Efficiency and Conservation Authority, Wellington.

Energy, U. S. Department of, 2000a. *"International Performance Measurement and Verification Protocol (IPMVP) Volume I: Concepts and Options for Determining Energy Savings"*, Office Of Energy Efficiency And Renewable Energy, U. S. Department of Energy, Washington D.C., USA.

Energy, U. S. Department of, 2000b. *"International Performance Measurement and Verification Protocol (IPMVP) Volume II: Concepts and Practices for Improved Indoor Environmental Quality"*, Office Of Energy Efficiency And Renewable Energy, U. S. Department of Energy, Washington D.C., USA.

Fanger, P. O. 1971. *"Thermal Comfort"* , McGraw-Hill, New York, USA.

Fitzgerald, G. and Ryan, G. 1996. *"Factors in Appliance - Circuit Level Domestic Electricity Consumption"*, A report by Fitzgerald Applied Sociology and Industrial Research Limited, Christchurch.

Flanagan, S. 1998. *"BRANZ Microvolt Logger: Design Notes and Software"* , Internal BRANZ Technical Report, BRANZ, Judgeford.

Fuller, T. and Minogue, P. 1981. *"Efficiency and Energy Conservation Potential of Domestic Heating Systems"*, A report by An Foras Forbartha, Dublin, Ireland.

Gagge, A. P., Fobelets, A. and Berglund, L. G. 1986. *"A Standard Predictive Index of Human Response to the Thermal Environment"*, ASHRAE Transactions, No. 92, Part 2B, pp. 709-731.

Harrison, J. R., Ackery, E. M. and Wills, D. R. 1952. *"Symposium on Church Heating"* , Journal of the Institution of Heating and Ventilating Engineers, pp. 71–126.

Hearfield, M. and Cox-Smith, I. 1998. *"Physics Section DVM HP 34401A"* Calibration Report, BRANZ, Judgeford, Wellington.

Howarth 1985. *'Predictions of Temperature Distributions Within Spaces with Convective Heat Sources"*, Proceedings of the CLIMA2000 World Congress on Heating Ventilation and Air-Conditioning, pp. 389 – 394, held 25-30 August 1985, Copenhagen, Denmark.

Hunt, D. R. G. and Gidman, M. I. 1982. "*A National Field Survey of House Temperatures*", Building and Environment, Vol. 17, No. 2, pp. 107-124.

Inard, C., Bouia, H. and Dalicieux, P. 1996. *'Prediction of Air Temperature Distribution in Buildings with a Zonal Model"*, Energy and Buildings Vol. 24 pp. 125-132.

Innova 1997. *'Thermal Comfort"* , website http://www.innova.dk/books/thermal/thermal.htm, Innova AirTech Instruments, Ballerup, Denmark.

IPCC 2001. *'Summary for Policymakers"* , A Report of Working Group I of the Intergovernmental Panel on Climate Change.

IRL 1992. *'Report on the Calibration of a Sample of Thermocouple Wire Report No. Temperature/92/001, 28 July 1992"*, Measurement Standards Laboratory, Industrial Research Limited, Lower Hutt, Wellington.

IRL 1995. *'Report on the Calibration of a Platinum Resistance Thermometer Report No. Temperature/95/168, 19 December 1995"*, Measurement Standards Laboratory, Industrial Research Limited, Lower Hutt, Wellington.

Isaacs, N. and Donn, M. 1989. *'Seasonality in New Zealand Mortality – The Influence of Buildings"*, Report CRP 50, Energy Research Group, School of Architecture, Victoria University, Wellington.

Isaacs, N. and Donn, M. 1994. *'Effects of Thermal Mass on Energy Consumption and Indoor Climate"*, Centre for Building Performance Research, Victoria University, Wellington.

Isaacs, N. P. 1998. *"Poverty and Comfort?"*, Presentation at the Fourth National Food Bank Conference, 13 November 1998, Wellington.

Isaacs, N. P. 1999. *'Building Science, Regulations and Health"*, Presentation– to the EECA Seminar 'Improving Health and Energy Efficiency through Healthy Housing', September 13-15 1999, Christchurch, Wellington, Auckland.

ISO 1984. *'ISO 77 30-1984 Moderate Thermal Environments – Determination of the PMV and PPD Indices and Specifications of the Conditions for Thermal Comfort"*, International Organisation for Standardization, Geneva, Switzerland.

ISO 1985. *"ISO 7726-1985 Thermal Environments – Instruments and Methods for Measuring Physical Quantities"*, International Organisation for Standardization, Geneva, Switzerland.

ISO 1993. *'Guide to the Expression of Uncertainty in Measurement",* International Organisation for Standardization, Geneva, Switzerland.

Jaques, R. 2000. *'Summertime Overheating in New Zealand Houses – Influences, Risks and Mitigation Strategies",* BRANZ Study Report 89, Judgeford.

Kimura, K. 1977. "*Scientific Basis of Air Conditioning*", Applied Science Publishers, Barking, England.

Lutzenhiser, L. 1992. *" A Cultural Model of Household Energy Consumption"*, Energy, Vol. 17 (1) pp. 47-60 (quoted in Bell *et al* 1996).

Lyberg, M. D. 1993. *'Building Thermal Performance: Techniques for Analysis, Auditing and Monitoring"*, The Swedish Institute for Building Research, Consortium for Advanced Learning on Energy and Environment, Gävle, Sweden.

Manly, B. F. J. 1994. "*Multivariate Statistical Methods, A Primer*", 2nd Edition, Chapman And Hall, London.

Mant, D. C. and Gray, J. A. 1986. *'Building Regulation and Health",* BR97, Report by the Building Research Establishment (BRE), Garston, England.

Mardia, K. V., Kent, J. T. and Bibby, J. M. 1979. *"Multivariate Analysis"*, Academic Press, London.

McIntyre, D. A. 1980. *'Indoor Climate"*, Applied Science Publishers, Barking, England.

Melikov, A K., Krüger, U., Zhou, G., Madsen, T. L. and Langkilde, G. 1997. "*Air Temperature Fluctuations in Rooms*", Building and Environment, Vol. 32, No. 2, pp. 101 -114.

Muncey, R. W. R. 1979. "*Heat Transfer Calcula tions for Buildings*", Applied Science Publishers, Barking, England.

National Health Committee 1998. "*The Social, Cultural and Economic Determinants of Health in New Zealand: Action to Improve Health*", National Advisory Committee on Health and Disability Report, Wellington

Newhall, C., Hendley II, J. W. and Stauffer, P. 1997. "*The Cataclysmic 1991 Eruption of Mount Pinatubo, Philippines*", US Geological Survey Fact Sheet 115-97, Cascades Volcano Observatory, Vancouver, Washington, USA.

Nicholas, J. V. and White, D. R. 1982. "*Traceable Temperatures*", DSIR Bulletin 234, Government Printer, Wellington.

Olesen, B. W., Schøler, M. and Fanger, P. O. 1979. "*Discomfort Caused by Vertical Air Temperature Differences*", pp 561-579, Indoor Climate, Danish Building Research Institute, Hørsholm, Denmark.

Olofsson, T. 1997. "*Building Energy Load Predictions – Based on Neural Network Techniques*", Licentiate Thesis, Umeå University, Sweden.

Omega Engineering 2001. "*Complete Temperature Measurement Handbook and Encyclopedi a*", Page Z-51, Technical Reference Section,
(downloaded from http://www.omega.com/temperature/Z/zsection.asp)

Oseland, N. A. and Humphreys, M. A. 1994. "*Trends in Thermal Comfort Research*", BR266, Report by the Building Research Establishment (BRE), Garston, England.

Penney, A. C. 1997. "*Climate Database (CLIDB) User's Manual*" , NIWA Technical Report 4, National Institute of Water and Atmospheric Research, Wellington. (see also http://katipo.niwa.cri.nz/www_cli.htm).

Pollard, A., Stoecklein, A. and S. Bishop 1997. "*Preliminary Findings on the Internal Temperatures in a Selection of Wanganui Houses*", Proceedings of the 1997 Mites Asthma & Domestic Design III Conference, Wellington.

Pollard, A. and Stoecklein, A. 1998a. "*Heating Energy and Temperatures in Heavy Mass Houses*", Proceedings of the 1998 IPENZ Conference, Vol. 2, pp. 57-61, Auckland.

Pollard, A. and Stoecklein, A. 1998b. "*Occupant and Building Related Determinants on the Temperature Patterns in New Zealand Residential Buildings*", Proceedings of the 1998 IPENZ Conference, Vol. 2, pp. 62-66, Auckland.

Pollard, A. 1999. "*The Measurement of Whole Building Energy Usage for New Zealand Houses*", Proceedings of the 1999 IPENZ Technical Conference, 11-12 July 1999, Auckland.

Pollard, A., O'Driscoll, R. and Pinder, D. N. 2001. "*The Impact of Solar Radiation on the Air Temperature within a Residential Building*", Paper to be presented at the ISES Solar World Congress, November 2001, Adelaide, Australia.

Potter, D. 1996. "*Measuring Temperatures with Thermistors - a Tutorial*", Application Note 065, National Instruments (downloaded from http://www.natinst.com/).

Raw, G. J. 1988. "*A Discussion Paper: Health and Hygrothermal Conditions in Homes*", Proceedings of the Healthy Buildings '88 Conference (editors: Berglund, B. and Lindvall, T.), pp. 479-488, Swedish Council for Building Research, Stockholm, Sweden.

Raw, G. J. and Hamilton, R. M. 1995. "*Building Regulation and Health*", BR289, Report by the Building Research Establishment (BRE), Garston, England.

Reddy, T. A. and Claridge, D. E. 1994. "*Using Synthetic Data to Evaluate Multiple Regression and Principal Component Analyses for Statistical Modelling of Daily Building Energy Consumption*", Energy and Buildings Vol. 21, No. 1, pp 35-44.

Saïd, M N. A., Zhang, J. S., Shaw, C. Y. and Christianson, L. L. 1995. "*Computation of Room Air Distribution*" ASHRAE Transactions, Vol. 101, Part 1, pp. 1065-1076.

Schiller, G. 1990. "*A Comparison of Measured and Predicted Comfort in Office Buildings*", ASHRAE Transactions, Vol. 96, Part 1, pp. 609-622.

Schooley, J. F. 1986. *"Thermometry"* CRC Press, Boca Raton, Florida, USA.

Seligman, C., Darley, J. M. and Becker, L. J. 1978. *"Behavioural Approaches to Residential Energy Conservation"*, Energy and Buildings, Vol. 1, No. 3, pp. 325-337.

Shorrock, L. D. and Henderson, G. 1990. *"Energy Use in Buildings and Carbon Dioxide Emissions"*, BR170, Report by the Building Research Establishment (BRE), Garston, England.

Socolow, R. H. 1978. *"The Twin Rivers program on energy conservation in housing: Highlights and Conclusions"*, Energy and Buildings, Vol. 1, No. 3, pp. 207-242.

Sonderegger, R. C. 1978. *"Movers and Stayers: The Resident's Contribution to Variation across Houses in Energy Consumption for Space Heating"*, Energy and Buildings, Vol. 1, No. 3, pp. 313-324.

Spielvogel, L G. and Rudin, A. 1984. *"Religious Building Energy Use"*, ASHRAE Journal, January 1984, pp. 40–45.

Spielvogel, L G. and Rudin, A. 1988a. *"Religious Building Energy Use – An Update"*, ASHRAE Journal, February 1988, pp. 34-42.

Spielvogel, L G. and Rudin, A. 1988b. *"Energy Considerations for New Religious Buildings"*, The Construction Specifier, Vol. 10, October 1988, pp. 84–96.

Standards New Zealand 1977. *"NZS4218P:1977 Minimum Thermal Insulation Requirements for Residential Buildings"*, Standards New Zealand, Wellington.

Standards New Zealand 1982. *"NZS4220:1982 Code of Practice for Energy Conservation in Non-Residential Buildings"*, Standards New Zealand, Wellington.

Standards New Zealand 1996 *"NZS4218:1996 Energy Efficiency – Housing and Small Building Envelope"*, Standards New Zealand, Wellington.

Standards New Zealand 1996 *"NZS4243:1996 Energy Efficiency – Large Buildings"*, Standards New Zealand, Wellington.

Statistics, New Zealand Department of, 1973. *'Report on the Survey of Household Electricity Consumption 1971-72"*, Government Printer, Wellington.

Statistics, New Zealand Department of, 1976. *'Survey of Household Elec tricity Consumption 1971-72: Report on the Temperature/Insulation Study"*, Government Printer, Wellington.

Steinhart, J. S. and Hart, S. R. 1968. Deep-Sea Res. **15** 497 (quoted in Schooley 1986).

Stoecklein, A. 1995. *'Report on the Development of Acceptable Solutions for Clause H1 of the New Zealand Building Code (Housing)"*, Report by the Building Research Association of New Zealand, Judgeford, Wellington.

Stoecklein A., Pollard, A., Isaacs, N., Ryan, G., Fitzgerald, G., James, B., and Pool, F. 1997a. "*Energy Use in New Zealand Households: Report on the Household Energy End Use Project (HEEP) Year 1*", Energy Efficiency and Conservation Authority, Wellington.

Stoecklein A., Pollard, A., Bishop, S., Isaacs, N., Ryan, G., and Sanders, I. 1997b. "*Energy Use in New Zealand Households: Year 1 Update Report on the Household Energy End-Use Project (HEEP)",* Energy Efficiency and Conservation Authority, Wellington.

Stoecklein, A., Pollard, A., James, B. and Ryan, G. 1997c. "*Multi Disciplinary Investigation of Energy Use in New Zealand Households*", IPENZ Transactions, Vol. 24, No. 1/CE, November 1997, pp. 64-73.

Stoecklein, A., Pollard, A. and Bishop, S. 1998a. "*Energy End-Use in New Zealand Houses*", Proceedings of the 1998 ACEEE Conference, Panel 1, pp 343-354 Asilomar, USA.

Stoecklein A., Pollard, A., Isaacs, N., Bishop, S., James, B., Ryan, G. and Sanders, I. 1998b. "*Energy End-use and Socio/Demographic Occupant Characteristics of New Zealand Households*", Proceedings of the 1998 IPENZ Conference Vol. 2, pp. 51 -56, Auckland.

Stoecklein, A. and Bassett, M. 1998c. "*A New Thermal Design Guide For New Zealand Houses"*, Proceedings of the 1998 IPENZ Conference Vol. 2, pp. 51-56, Auckland.

Stoecklein, A., Pollard, A. Tries, J., Camilleri, M., Isaacs, N. and Fitzgerald, G. 2000. "*Understanding Energy End-Use in New Zealand Houses*", Proceedings of the 2000 ACEEE Conference, Panel 1, Asilomar, USA.

Stoecklein, A, 2001. Internal Research Communication.

Stoops, J. L. 1998.*"Managing the Practical Challenges in a Large End-Use Metering Project: Methodology of Monitoring Energy Consumption in Dispersed Buildings. Operational Experiences, Protocols, Etcetera"*, Proc. of the Improving Electricity Efficiency in Commercial Buildings Conference, 21-23 September 1998, Amsterdam, The Netherlands.

Taylor, R., Smith, I., Cochrane, P., Stephenson, B. and Gibbs, N. 1997. *"The State of New Zealand's Environment 1997"*, The Ministry for the Environment and GP Publications, Wellington.

Todd, J. 2001. *"Woodheaters"*, http://www.acre.murdoch.edu.au/refiles/heaters/index.html, Website developed by the Australian Cooperative Research Centre for Renewable Energy (ACRE), Perth, Australia.

Tries, J., Stoecklein, A., Pollard, A., Camilleri, M. and Isaacs, N. 2000. *"Understanding Energy Use in New Zealand Homes"*, Proceedings of the Electricity Engineers' Association Annual Conference, 16-17 June 2000, Auckland.

Vale, B. and Vale, R. 2001 *"Thermal Performance of Superinsulated Lightweight Residential Construction in The Auckland Climate"*, Proceedings of the 2001 CIB World Building Congress, Wellington.

Van der Kooi, J. and Förch, E. 1985 *"Calculation of the Cooling Load by Means of a 'More-Air-Points-Model'"*, Proceedings of the CLIMA2000 World Congress on Heating Ventilation and Air-Conditioning, pp. 395- 401, held 25-30 August 1985, Copenhagen, Denmark.

Van der Werff, I., Amor, R. and Donn, M. 1990. *"Standard Data Files for Computer Thermal Simulations of Solar Low Energy Non-Residential Buildings"*, CRP 53, Energy Research Group, School of Architecture, Victoria University, Wellington.

Watt Committee (edited by Markus, T. A.) 1994. *'Domestic Energy and Affordable Warmth"* , Report Number 30, E& FN Spon, London.

Wheeling, T. and Palmiter, L. 1985. *'SUNCODE -PC v5.71"*, Ecotope Incorporated, Seattle, United States of America.

WHO 2000. *'Guidelines for Air Quality"* , World Health Organisation, Geneva, Switzerland.

Widegren-Dafgård, K. 1984. *"Are We Sensitive to Room Temperature",* page 10-12 of Indoor Climate, Swedish Council for Building Research, Stockholm, Sweden. (A translation from the periodical Byggforskning, 4, 1984.)

Williamson, A. 1997. *"Energy Efficiency in Domestic Dwellings: a Literature Review and Commentary"*, Report for the Ministry of Commerce, Thermocell Ltd., Christchurch.

Appendix A

Glossary and Abbreviations

ASHRAE: The American Society of Heating, Refrigeration and Air-conditioning Engineers.

Building Envelope: The part of the building structure that separates the conditioned space inside of a building from the outside environment.

CFD (Computational Fluid Dynamics): The mathematical determination of fluid motion based on known boundary or initial conditions.

clo Value: A derived unit; 1 clo = $0.155\ m^{2}\cdot K\cdot W^{-1}$. A numeric representation of a clothing ensemble's thermal resistance . 1 clo is approximately the insulation value of a business suit.

Coefficient of Determination (R^2): The ratio pf the sums of squares described by the model under question to the total sums of squares. For a single variable the coefficient of determination is equal to the square of the correlation coefficient.

Conditioned Space: The area generally occupied within a building that is heated or cooled so that it is comfortable for the occupants. Insulation is generally placed between the conditioned space and the outside environment.

Correlation Coefficient: The degree of linear association between two random variables.

Data Logger: A self-contained data acquisition system that incorporates data storage and retrieval.

DuBois Area (A_D): An estimation of a person's surface area from their height (h measured in m) and their mass (m measured in kg), $A_D = 0.202\cdot m^{0.425}\cdot h^{0.725}$

EECA: Energy Efficiency and Conservation Authority. A government agency concerned with ensuring the efficient use of energy in New Zealand.

Energy Service: The useful output, noticeable to the occupant, for which an energy input is applied. For example, the resulting indoor temperature is the energy service provided by the energy used for space heating.

Equipment Gains (see also Internal Gains): The heat generated within the conditioned space inside a building due to a by-product of the operation of equipment not primarily used for heating or cooling.

Expanded Uncertainty: An interval about a measurement which has a given degree of confidence of containing the value of the measurand. The expanded uncertainty is equal to the standard uncertainty multiplied by a coverage factor.

Heavy Mass (see also Thermal Mass): The high usage of building materials that have a high thermal heat capacity (usually through the material being more dense) in a particular building design. For example, a building constructed predominantly from brick or concrete is said to a heavy mass building.

HEEP: The Household Energy End-Use Project. A New Zealand measurement programme designed to provide estimates of residential energy use and energy service for a wide range of appliances and energy end-uses. This project includes the measurement of indoor temperatures within each sample house.

HERO (Home Energy Ratings Options): A building audit scheme that assesses the energy performance of a building by examining building geometry, insulation levels and other design features.

Infiltration: The movement of outside air through the cracks and joints, in the building envelope, to the conditioned space inside of a building.

Internal Gains (see also Equipment Gains): The unintentional heat generated within the conditioned space of a building due to the occupants' metabolic heat output.

Mean Radiant Temperature: The uniform temperature of an imaginary enclosure in which the radiant heat transfer is equal to the actual radiant transfer of the actual enclosure.

Metabolic Rate: Rate of energy production within the body. The metabolic rate varies with activity level and is normalised by the surface area of the person (see DuBois area). A derived unit called the met is used. 1 met = 58.2 $W \cdot m^{-2}$.

New Effective Temperature (ET*): The temperature of a uniform enclosure at 50% relative humidity, which would produce the same net heat exchange by radiation, convection and evaporation as the environment in question.

NZBC: The New Zealand Building Code.

Predicted Mean Vote (PMV): The predicted mean value of ASHRAE comfort votes of a large number of people subject to the specified environment.

Predicted Percentage Dissatisfied (PPD): A function of the Predicted Mean Vote (PMV) that gives the number of people likely to be dissatisfied with the specified environment.

Principal Component Analysis (PCA): A data reduction technique that makes a sequence of the most important linear combinations of a set of variables.

R^2: (see Coefficient of Determination).

R-value: The thermal resistance a building material, scaled by surface area, to heat flow. The units for R-value are given as $m^2 \cdot K \cdot W^{-1}$.

Sensor: A transducer element that may incorporate additional componentry to allow for input into a datalogger.

Skewness: The degree of asymmetry in the density distribution of a variable.

Standard Uncertainty: An estimate of the standard deviation of the measurand.

Takeback: The reduction in expected energy savings due to an efficiency improvement arising from the user taking a higher level of utility from the energy service. For example, there is full takeback of heating energy savings from adding additional insulation when just as much energy is used for heating than before, while there is an corresponding improvement to the indoor temperatures (the energy service of heating).

Thermal Bridge: A pathway through the building envelope of lower thermal resistance than for the majority of the building surface. Consequently a disproportionate amount of the heat flow will flow along this pathway.

Thermal Comfort: That condition of mind which expresses satisfaction with the thermal environment.

Thermal Mass (see also Heavy Mass): The thermal heat capacity of a building. For example, a heavy mass building is said to be a buildings with a high thermal mass.

Transducer (see also Sensor): A device that provides a usable output in response to a specific measurand.

Appendix B

CD Contents

Directory	**Contents**
/Biblio	Electronic documents used for the preparation of this thesis and of background interest (mainly in PDF or HTML)
/CV	The author's curriculum vitae
/Data	The temperature data collected from All Saints Church. Other miscellaneous data.
/Extras	Miscellaneous files of background interest.
/Thesis	A PDF copy of this thesis. A poster presented on the temperatures in All Saints Church at the 1999 NZIP Conference, Wellington. A paper to be presented at the 2001 ISES World Congress, Adelaide.
/Viewers	Microsoft Windows programs to allow for the viewing of PDF files, powerpoint presentations, and word documents.

Appendix C

Producing a suitable calibration environment

The calibration of air temperature loggers can be undertaken by placing the loggers in a well-mixed fluid that is also subject to a reference temperature measurement. ASHRAE (1987) provides guidance on the causes of error and amongst others suggests consideration should be given to:

1. Heat flow (conductive, convective and radiative) to the enclosure
2. Uniform velocity and temperature at measured location
3. Thermal storage of the enclosure should not influence measurement.

An environmental range of between 5°C and 25°C was considered appropriate as the temperature loggers were to be primarily used to study winter conditions in houses. For monitoring households during the summer the upper end of this range may need to be extended.

An immersion bath containing a paraffin-based oil was examined as a calibration environment. This calibration bath is typically used to calibrate liquid-in-glass stem thermometers. A picture of this set-up during calibration is shown in Figure C.1. The advantage of the oil bath is that the oil can be well mixed and it would be expected that the temperature set-points would be quickly established however in order to weight down the rack used to hold the loggers a large iron weight was used. This weight would add to the thermal inertia of the system and slow down the speed at

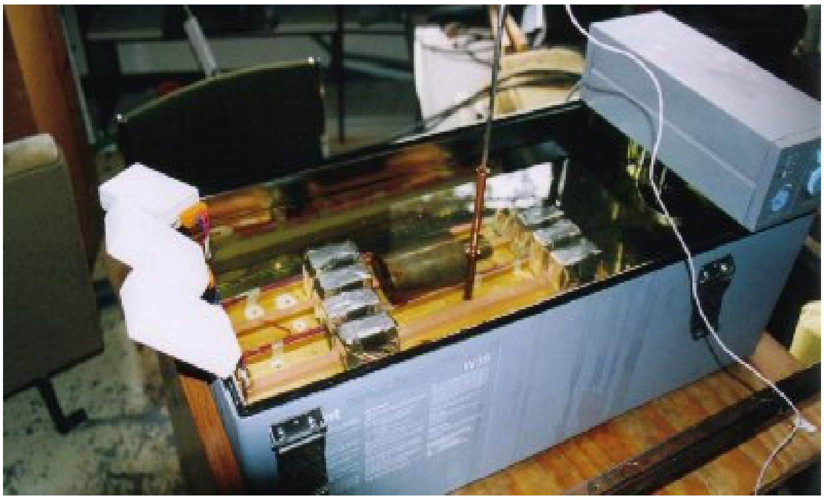


Figure C.1 Oil calibration bath

which equilibrium was reached. As the loggers are electronic devices they are not suited to being immersed in liquids so each logger was put into a polyethylene bag before being submerged in the oil. This "waterproofing" significantly lengthened the set -up time for the calibration. It was intended to use three temperature set-points for the calibration of 5°C, 15°C and 25°C.

The calibration bath also has a separate cooling unit to reduce the oil temperature. After establishing a 5°C set-point the cooling compressor tripped a fuse causing a loss of power to the computer monitoring the PRT and so losing the reference temperature data. As all reference data had been lost it was decided to abandon the calibration run. After retrieving the ten temperature loggers it was discovered that the "waterproofing" of four of these loggers had failed and that these loggers were contaminated with oil. Fortunately after removing the oil the loggers proved to be operational and could be re-used however it was decided to set aside the immersion bath method owing to the practical difficulties encountered during this calibration and to explore other methods.

Air was used in place of oil as the heat transfer medium. Using a gas instead of a liquid reduces the conductive heat transfer from the medium to the temperature loggers making the process more important. As the conductive heat transfer is reduced the radiative heat transfer from the walls of the calibration chamber become relatively more important.

The Guarded Rotatable Hotbox (see Figure C.2) is a controlled environment at BRANZ primarily used for thermal insulation testing. The Hotbox was used as the calibration chamber for the air calibrations of the temperature loggers.

Figure C.2 Guarded Rotatable Hotbox

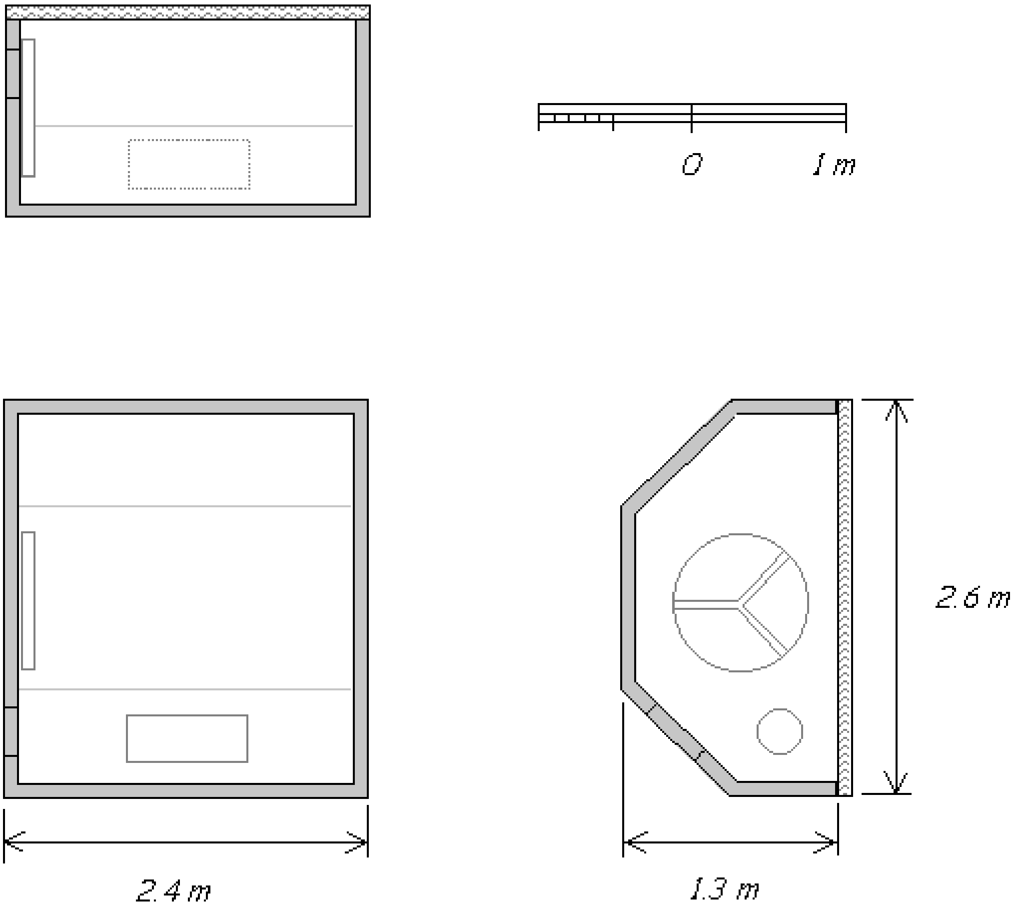


Figure C.3 Dimensions of the Guarded Rotatable Hotbox (Scale 1:50)

The calibrations used thermocouples to verify the environment across the sample. The temperature loggers were placed on a wooden frame (shown in Figure C.4). This wooden frame

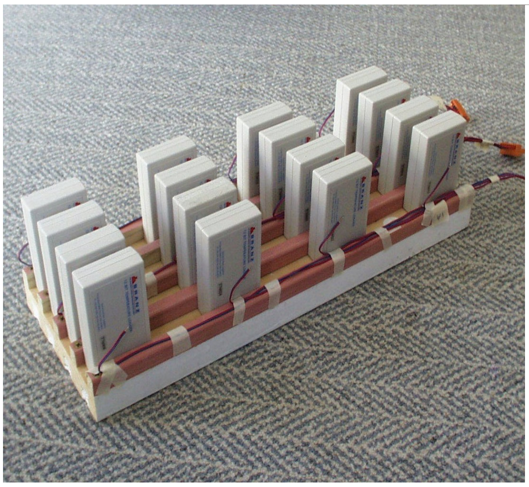


Figure C.4 Base used for calibration D

Figure C.5 Radiation shield used for calibration D was placed on an insulated base with a sheet of stainless steel acting as a radiation shield extending over it (shown in Figure C.5). This arrangement was placed within the Guarded Rotatable Hotbox chamber with the duct fan directed through the 'barn'. The chamber mixing fans were not used instead the airflow from the inlet duct was used to mix the air across the sample.

For the initial calibration in the Hotbox (D), a temperature ramp from 5°C to 30°C was used with a compensation applied to all the measurements to account for the thermal lag of each sensor (see section 3.4). The speed of ramping was a slow 1°C per hour. The difference between the thermocouple temperature and the reference Platinum Resistance Thermometer (PRT) temperature is shown in Figure C.6 with the red line showing the PRT temperature as indicated by the scale on the right hand side of the graph. The thermocouple temperatures are not stable indicating that there were problems with this calibration to maintain the consistency of the temperatures across the sample area.

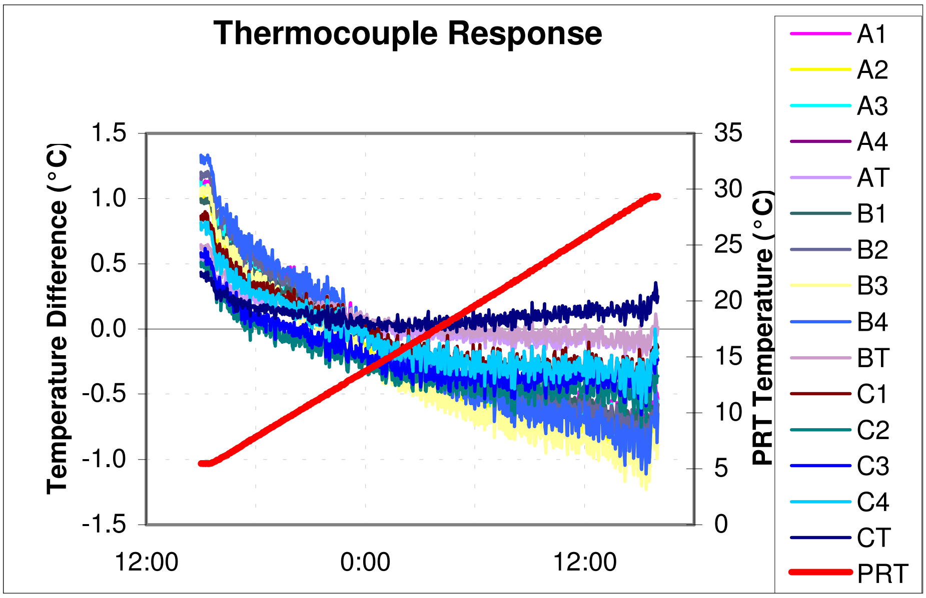


Figure C.6 Difference of the thermocouple temperatures from the PRT temperatures.
The response of the PRT is shown in red and its values are shown on the scale on the right hand side

To reduce the difference in temperatures between the medium and the chamber walls the temperature loggers were relocated closer to the centre of the chamber (shown in Figure C.7) and the mixing fans within the chamber were engaged. Each logger was wrapped in foil to further reduce the radiative heat transfer however latter calibration revealed that this was not necessary. The loggers were placed on an insulating base (shown in Figure C.8).

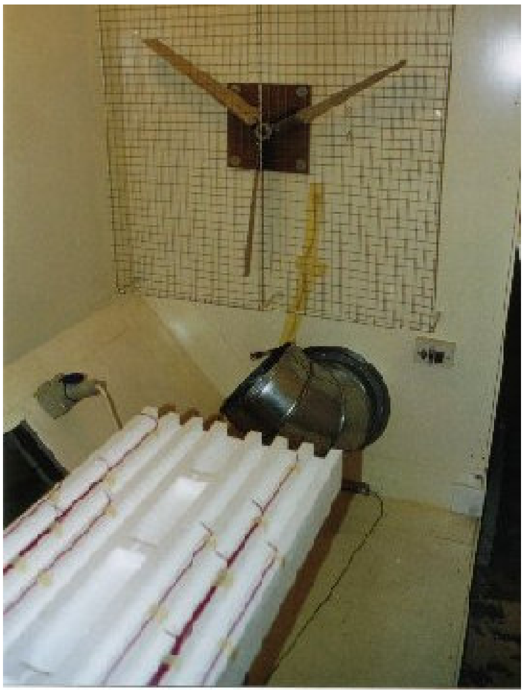


Figure C.7 Inside of Guarded Rotatable Hotbox
with base relocated to the centre of the chamber

Rather than ramping the temperature, three fixed temperature set-points were used (5°C, 15°C, 25°C) with the Guarded Rotatable Hotbox left to stabilise at each set-point. The calibration was undertaken during winter and the initial temperature set point at 5°C. The hot box was left overnight and the 5°C set-point measurement was made from about 8:00 am in the morning. Each set-point measurement covered a period of thirty minutes with each logger recording thirty one-minute readings. The two remaining set-points were measured during the day with stable conditions achieved for about two hours.

The temperature difference across the calibration sample as measured by the thermocouples is shown in Figure C.9. The 5°C set-point is seen to be stable due to the long time the environment was at this temperature and the similar ambient temperatures in the laboratory housing the Hotbox (which is not climate controlled). The 15°C and 25°C set-points were less stable than the 5°C set-point.

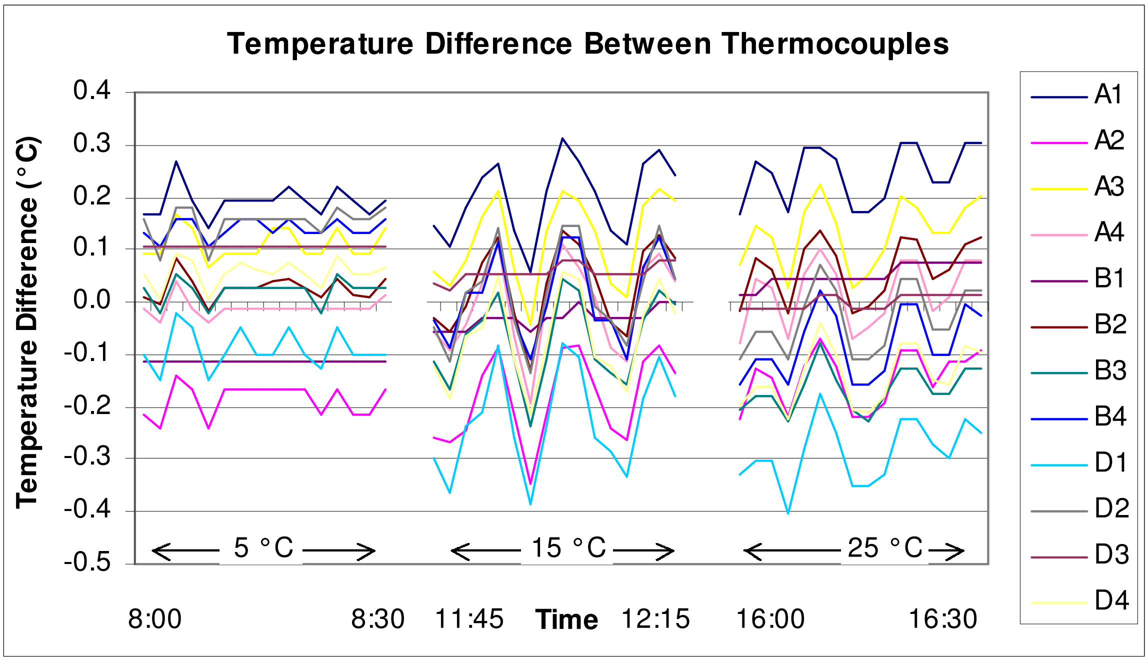


Figure C.9 Temperature difference across the calibration sample at the three temperatures set-points.

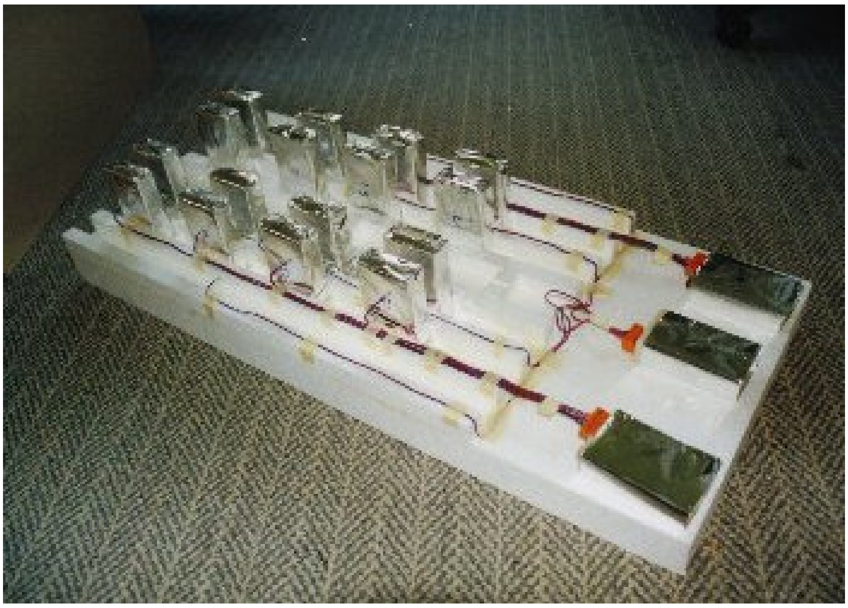


Figure C.8 Insulated base

The mean value of the temperature differences from the set-points was 0.0°C. As the mean value of the temperature differences is close to zero, the standard deviation of the temperature differences across the sample could be taken as a good representation for the consistency of the calibration environment. This standard deviation had a value of approximately 0.14°C. It should be noted that this consistency of the calibration environment (0.14°C) is dependent on the uncertainties from the thermocouples measuring the environment as well as the variation of the temperature of the calibration environment itself. The uncertainty from the thermocouple measurement was estimated in section 3.6.3 to be 0.14°C so the temperature variation across the calibration sample is likely to be small.

The hotbox has been seen to be a practical and accurate calibration environment for the calibration of a number of temperature loggers at one time. A consistent environment is maintained across the calibration sample when the calibration sample is located centrally within the hotbox chamber, the chamber mixing fans are in operation and sufficient time is allowed for the environment to stabilise. The consistency of the environment achieved across the calibration sample was better than 0.14°C.

Appendix D

Residuals of the Fitted Vertical Temperature Distribution

To examine the quality of the fit of Equation (6.3) to the measured vertical temperature distribution data from the Palmerston North and Whitby houses examined in Chapter 5, an analysis of the residuals from the fitting procedure will be examined.

Figure D.1, Figure D.2 and Figure D.3 show histograms of the residuals for each height for each of the sets of data and Table D.1, Table D.2 and Table D.3 give summary statistics for the residuals. Typically the standard deviation of a variable would give a measure of the uncertainty in that variable however as the residuals should be zero it is the variation about zero and not the variation about the mean (which is what the standard deviation gives) may be a better measure of uncertainty. For this reason the second moment about zero (which compares with the variance) and the square root of the second moment about zero (which compares with the standard deviation) are used in place of the variance and standard deviation respectively in these tables.

For Palmerston North and summer Whitby data the square root of the second moment about zero is small with a value of approximately 0.1°C. For the winter Whitby data the this value has a higher value of approximately 0.2°C

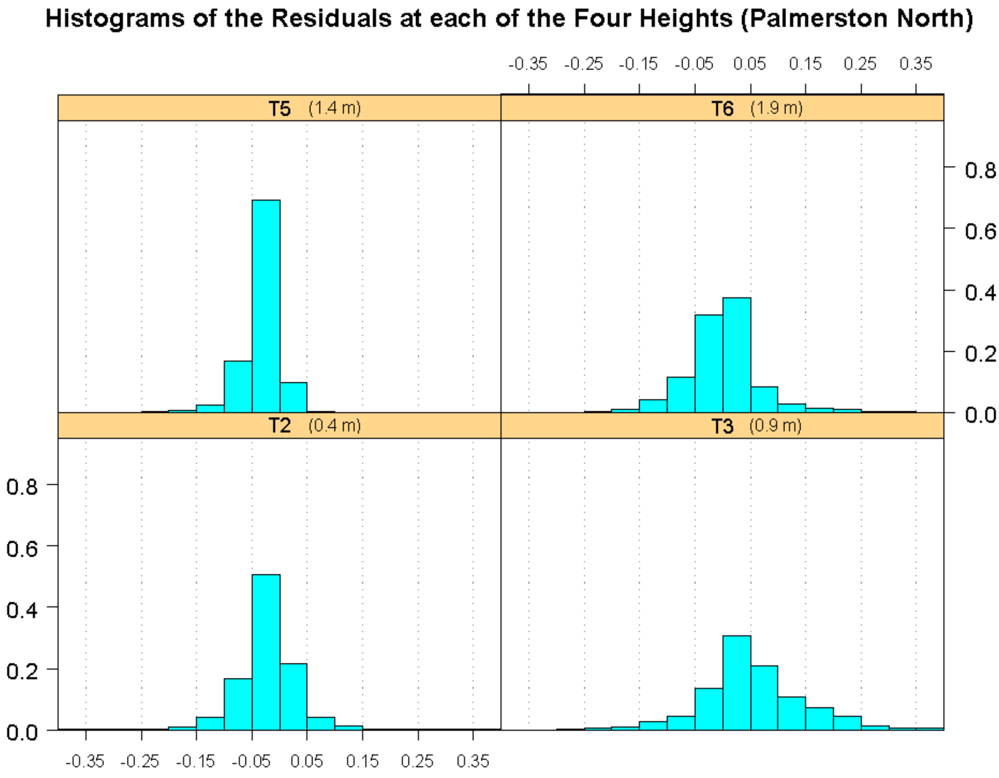


Figure D.1 Histograms of the residuals at each height for the Palmerston North data.

Table D.1 Summary statistics of residuals at each height for the Palmerston North data.

	T2	**T3**	**T5**	**T6**	**Pooled**
Minimum:	-.20	-.39	-.27	-.23	-.39
1st Quartile.:	-.04	.00	-.05	-.03	-.04
Mean:	-.02	.05	-.03	.00	.00
Median:	-.02	.04	-.03	.00	-.01
3rd Quartile.	.00	.10	-.02	.03	.03
Maximum:	.19	.42	.11	.34	.42
Second Moment About Zero (SM):	.00	.01	.00	.00	.01
Square Root of SM:	.05	.11	.05	.06	.07
Skewness:	.07	.07	1.51	.77	1.02
Kurtosis:	1.72	1.54	7.36	3.37	3.60

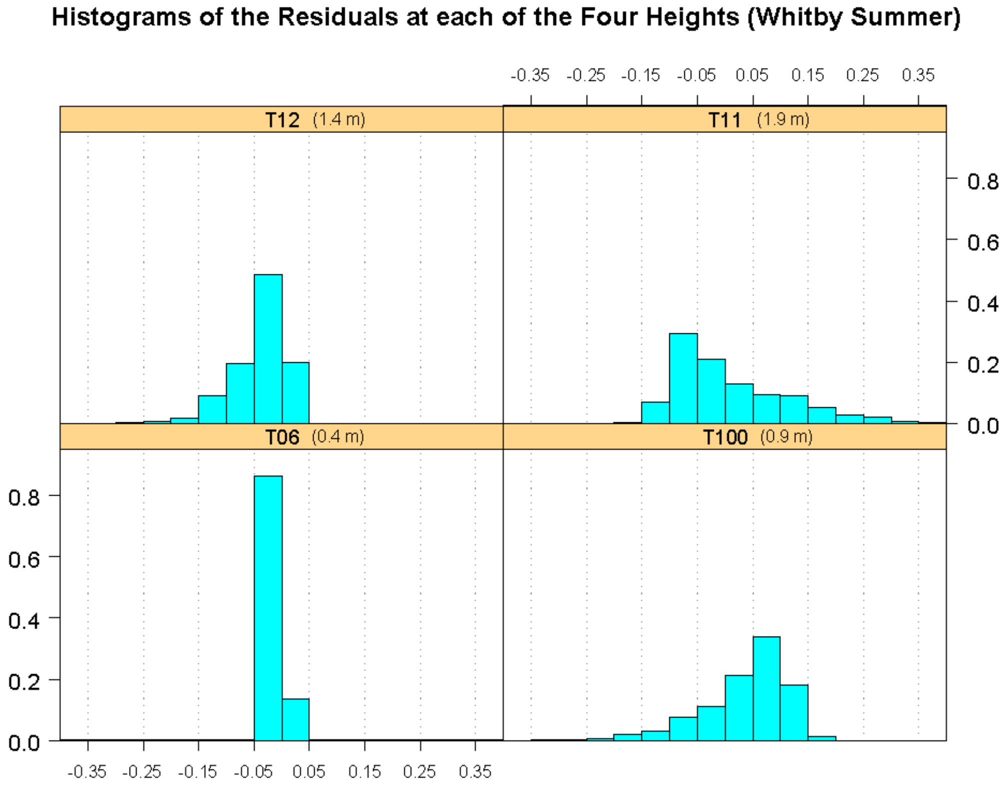


Figure D.2 Histograms of the residuals at each height for the Whitby summer data

Table D.2 Summary statistics of residuals at each height for the Whitby summer data.

	T06	**T100**	**T12**	**T11**	**Pooled**
Minimum:	-.04	-.54	-.39	-.16	-.54
1st Quartile.:	-.02	-.00	-.06	-.07	-.04
Mean:	-.01	.04	-.04	.01	.00
Median:	-.01	.06	-.03	-.02	-.01
3rd Quartile.	-.01	.09	-.00	.08	.03
Maximum:	.16	.20	.39	.87	.87
Second Moment About Zero (SM):	.00	.01	.00	.01	.01
Square Root of SM:	.02	.09	.06	.11	.08
Skewness:	2.25	1.59	0.95	1.67	1.19
Kurtosis:	16.26	4.45	5.37	4.74	8.21

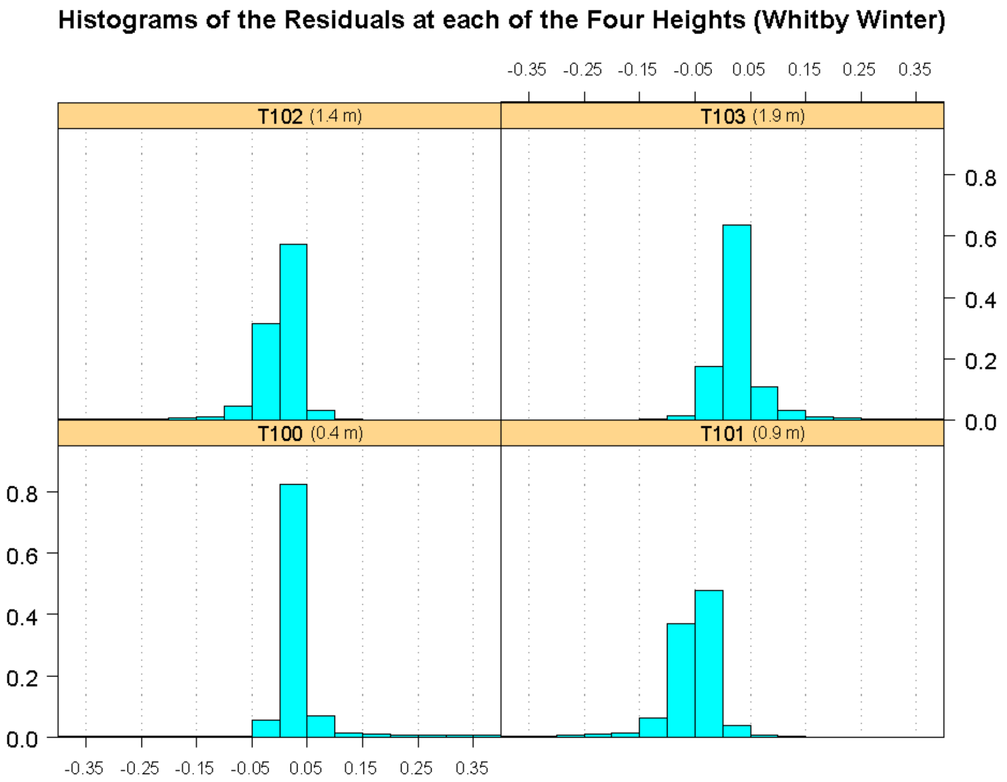


Figure D.3 Histograms of the residuals at each height for the Whitby winter data

Table D.3 Summary statistics of residuals at each height for the Whitby winter data.

	T100	**T101**	**T102**	**T103**	**Pooled**
Minimum:	-.21	-1.80	-2.10	-.55	-2.11
1st Quartile.:	.01	-.08	-.02	.01	-.03
Mean:	.05	-.10	-.04	.08	.00
Median:	.02	-.05	.01	.02	.01
3rd Quartile.	.03	-.03	.02	.04	.03
Maximum:	1.13	.35	.51	2.75	2.75
Second Moment About Zero (SM):	.02	.04	.04	.08	.04
Square Root of SM:	.12	.21	.19	.27	.21
Skewness:	4.65	4.41	5.38	5.05	0.97
Kurtosis:	25.26	22.57	35.14	30.34	36.67

To examine the effects of only collected temperature information from only two heights, instantaneous vertical temperature distributions were calculated for each of the three datasets using only the data from the loggers positioned at 0.4 m and at 1.9 m. The residuals were then calculated for the measurements at 0.9 m and 1.4 m (as the fitted function is a two parameter function and only two data points fitted, the residuals at 0.4 m and 1.9 m were zero)and the pooled estimates are shown in Table D.4.

Table D.4 Summary statistics of the pooled residuals from the fitting of the measurement of only the high and low temperature sensors for each of the sets of data.

	Palmerston North	**Whitby (Summer)**	**Whitby (Winter)**
Minimum:	-.62	-.43	-1.02
1st Quartile:	-.07	-.11	.01
Mean:	-.02	.01	.14
Median:	-.01	-.03	.05
3rd Quartile:	.05	.11	.09
Maximum:	.60	1.37	4.63
Second Moment About Zero (SM):	.02	.03	.18
Square Root of SM:	.13	.18	.43
Skewness:	.20	1.50	4.97
Kurtosis:	2.72	4.08	29.86

It can be seen that the square root of the second moment about zero is greater that for the fits using all the data but still has a good value of approximately 0.2°C for the Palmerston North and summer Whitby data and 0.4°C for the winter Whitby data.

Appendix E

The Principal Components of the Temperature Sample

The coefficients of the first three principal components of the difference from the mean temperature from the detailed temperature sample discussed in Section 7.3 are shown in Figure E.1, Figure E.2 and Figure E.3.

The factors covered by the principal components are difficult to generalise but appear to include a contrast between the living room loggers and the loggers from rooms away from the living room (The master bedroom is frequently located away from the living room, see principal component 1), a contrast between loggers placed at a high height and loggers placed at a low height and a contrast between the living room loggers and the kitchen/dining room loggers.

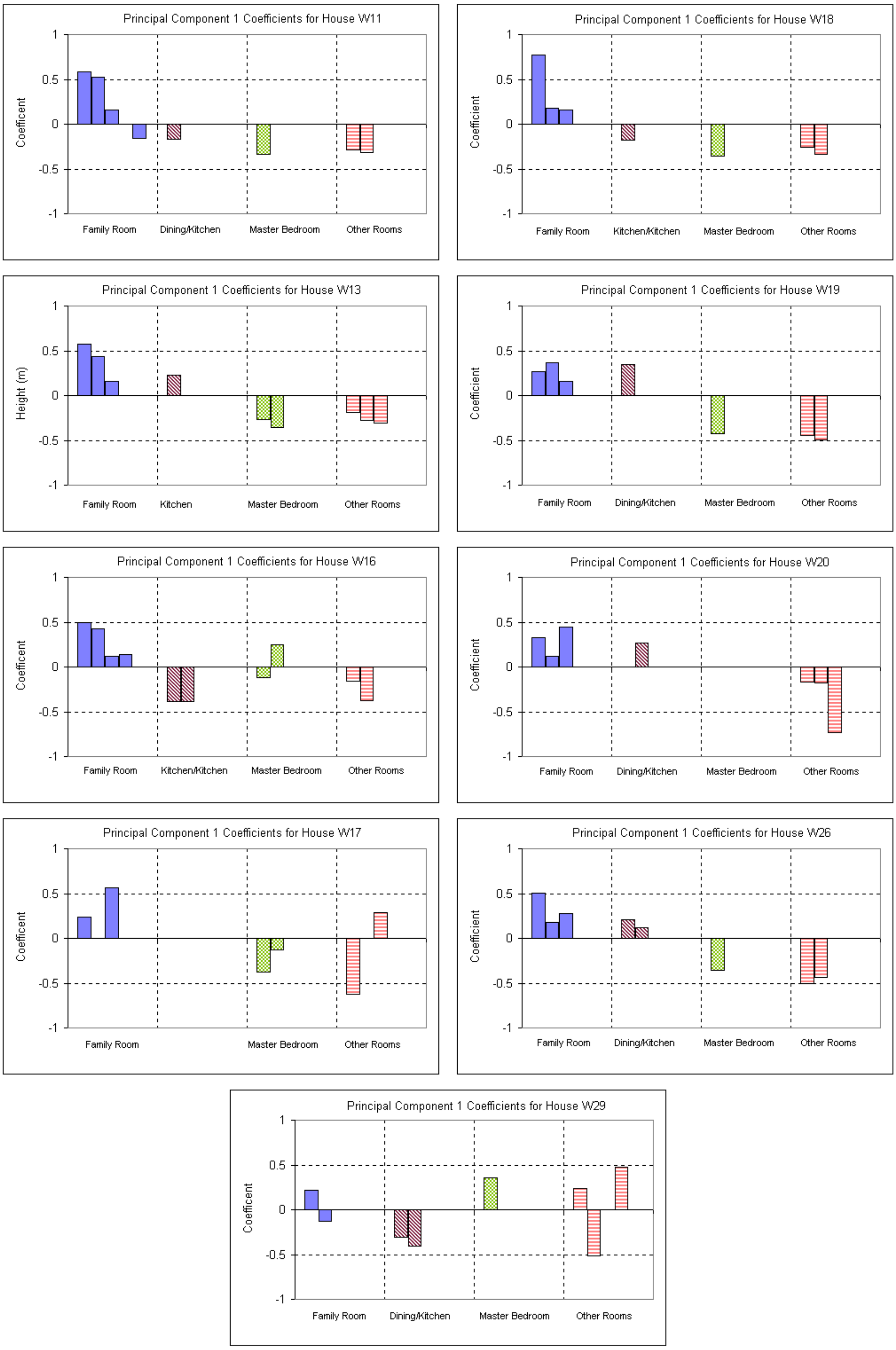


Figure E.1 Coefficients for principal component 1 from the detailed temperature houses.

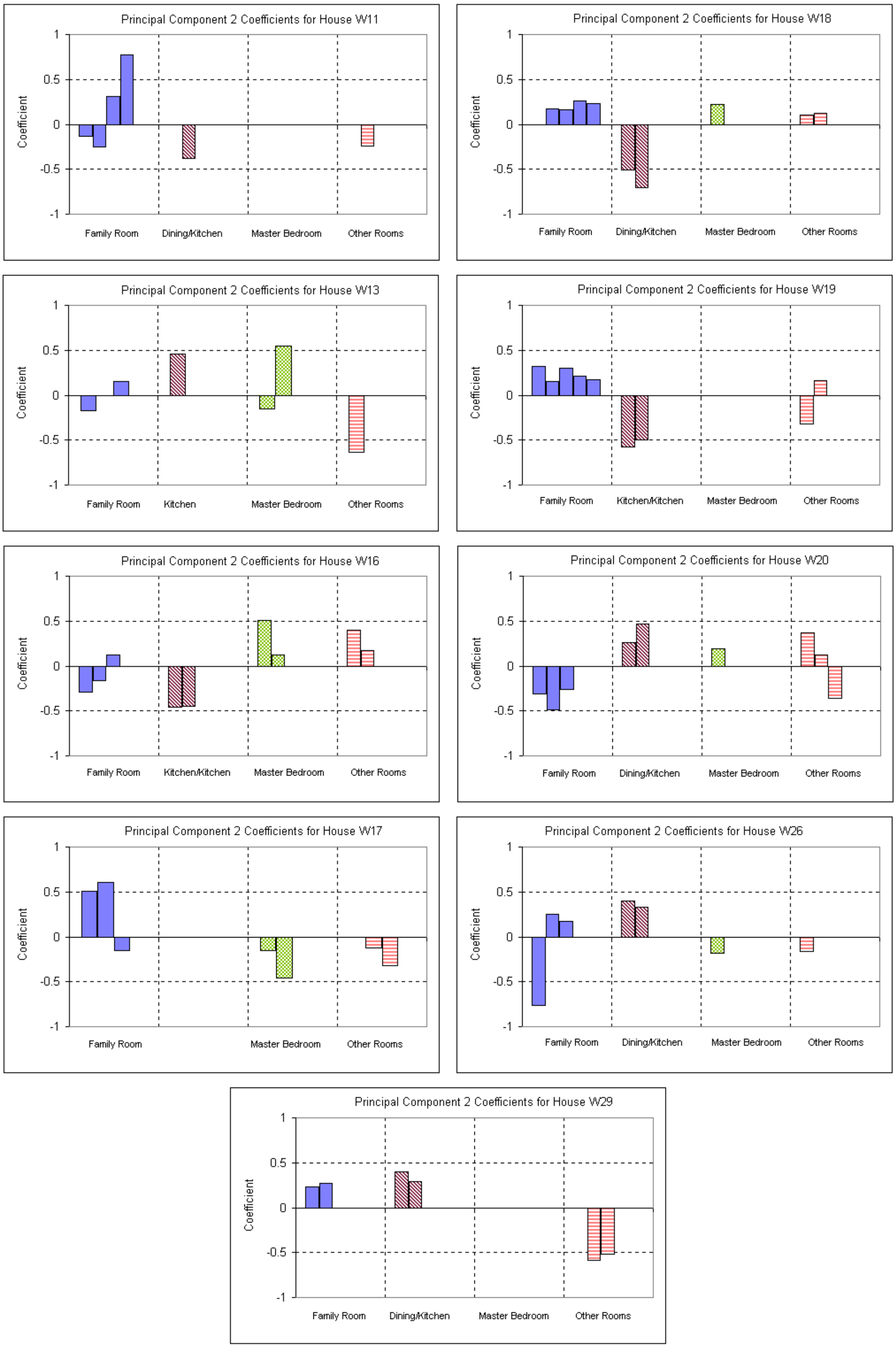


Figure E.2 Coefficients for principal component 2 from the detailed temperature houses.

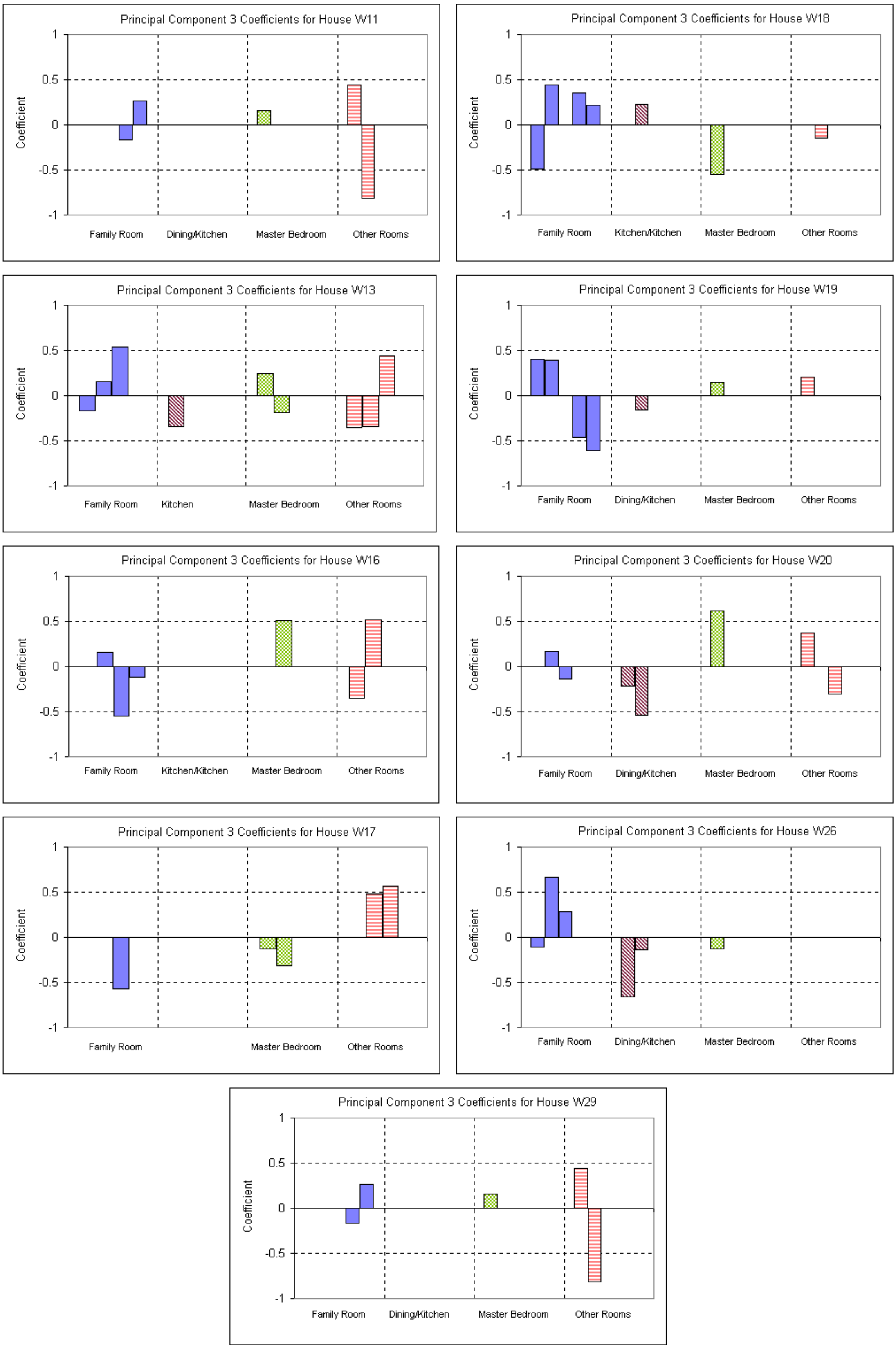


Figure E.3 Coefficients for principal component 3 from the detailed temperature houses.