AUSTRALIAN
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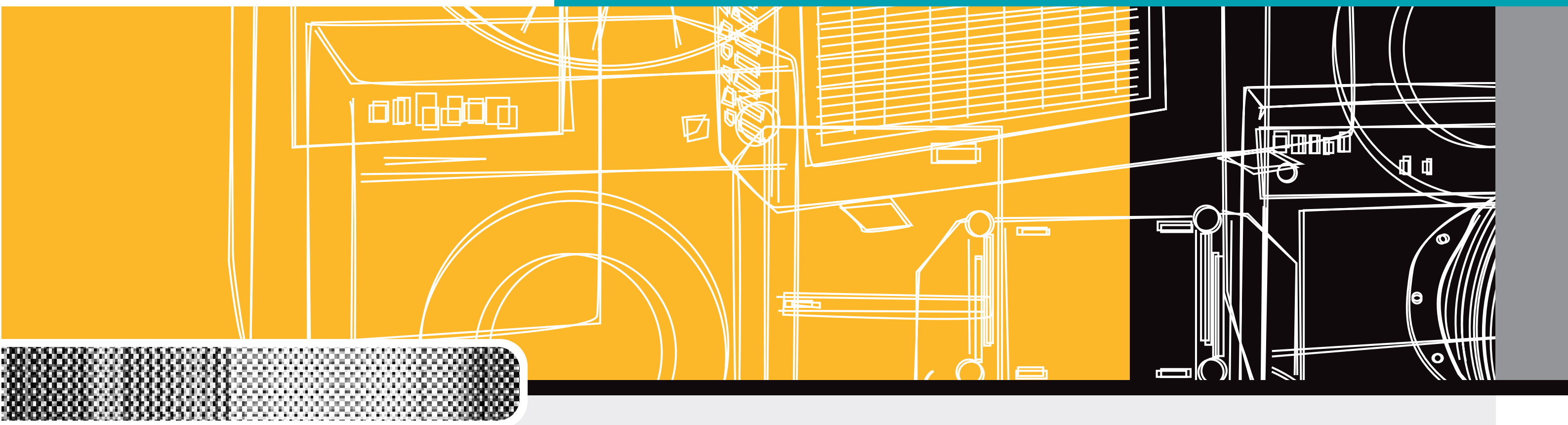
NATIONAL APPLIANCE AND EQUIPMENT
ENERGY EFFICIENCY PROGRAM

APPLIANCE ELECTRICITY END-USE: WEATHER AND CLIMATE SENSITIVITY



AN ANALYSIS OF 1993/94 RESIDENTIAL END-USE DATA IN NEW SOUTH WALES

Appliance Electricity End-Use:

Weather and Climate Sensitivity

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FOREWORD

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The issue of weather and climate, and its impact on household energy consumption, is a complex one and to date little research in Australia has been conducted in this area. A wide range of factors can affect energy demand on a day to day basis apart from just the weather itself – whether or not heating and cooling appliances are installed, whether the occupant is at home for all or part of the day, and the inherent energy efficiency of the housing shell itself.

The NSW electricity industry collected half-hourly electricity consumption data for a large number of individual appliances in a number of Sydney households during the period 1993/94 to assist in their load forecasting and planning. The Australian Greenhouse Office is grateful to Energy Australia and Integral Energy for making these data available for research purposes.

The Australian Greenhouse Office commissioned Macquarie University to produce this report based on research undertaken by Melissa Hart, an honours student at Macquarie University, and her supervisor, Richard de Dear. Energy consumption of selected appliances has been cross-matched with corresponding meteorological data to assess weather sensitivity.

As expected, the study has found that heating and cooling appliance use is strongly correlated with ambient temperature and to some degree other factors such as wind and humidity. However, detailed statistical analysis in this report has partly quantified this relationship. Analysis also showed that there was a correlation between ambient temperature and energy consumption of water heaters and refrigerators and freezers.

This report provides a number of new insights into the factors that affect household energy consumption in Australia and will be a valuable addition to the data inputs required for stock modelling and forecasting of future energy consumption and greenhouse emissions in the residential sector in Australia.

Gwenyth Andrews

Gwen Andrews
Chief Executive
Australian Greenhouse Office

The lead Commonwealth agency on greenhouse matters

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ACKNOWLEDGEMENTS

The authors would like to thank the Australian Greenhouse Office's Energy Efficiency Team, particularly Tony Marker and Shane Holt, for presenting us with an intriguing problem and facilitating our access to the unique NSW residential energy survey dataset. Lloyd Harrington of Energy Efficient Strategies is thanked for his critiques on the various drafts of this report and his countless insights along the way. Observed weather data used in this project were purchased from the Australian Bureau of Meteorology. The CSIRO's Division of Atmospheric Research, particularly Drs Kevin Hennessy and Jack Katzfey, kindly supplied DARLAM Climate Model data.

EXECUTIVE SUMMARY

The following report uses data from a Residential Energy Study (RES) conducted in the mid-Nineties to examine the weather and climate sensitivity of various household appliances. Individual appliance end-use data from the RES, collected at an interval of 30 minutes within 136 houses in the Sydney region, were analysed in conjunction with simultaneous weather data collected locally at the same sample frequency. Statistical relationships deduced between outdoor weather and individual appliance energy consumption were used to define the quantitative weather and climate sensitivities of appliance energy consumption. These observed sensitivities were then applied to long-term climatological observations (1961-1990) and future greenhouse climate scenario predictions (2031-2060). These analyses underpin a discussion of the potential impacts of climate change on household appliance energy end-use in the Sydney region.

Human thermal climatic indices such as effective temperature (ET*), standard effective temperature (SET) and simple air temperature degree-days were used to quantify the dependence of household appliance energy consumption on outdoor weather. The mean daily temperature associated with minimum heating and cooling energy consumption for Sydney indicated that a degree-day base temperature of 18°C was the most appropriate base temperature for the calculation of both heating and cooling degree-days. This finding is among the first empirical supports for adopting a constant year-round base temperature in degree-day calculations in Australia.

Appliances analysed in this project include: air-conditioners, room heaters, refrigerators, freezers and domestic hot water systems, all of which exhibited some degree of weather sensitivity, particularly space heating and cooling devices. For example 59% of day-to-day variance in air conditioning (cooling mode) energy end-use was accounted for by outdoor weather fluctuations. That is, outdoor weather is about 50% more influential over day-to-day variations in electricity consumption for cooling than all other factors combined (including day-of-week, fluctuations in occupancy level, individual levels of thermal comfort and nature of the household building shell). For room heaters the corresponding amount of day-to-day variance in electricity end-use explained by its association with weather outdoors was 63%. For refrigerators and freezers the weather-related variance amounted to 42% and 67% respectively.

Of the various indices of human thermal climate, the Standard Effective Temperature (SET) had the strongest correlation with electricity consumption of air-conditioners in cooling mode (R^2=59%). This finding was taken to indicate that thermal comfort parameters such as humidity and wind speed have an influence on the behavioural processes determining coolers' usage, over and above the basic human sensitivity to air temperature. Higher outdoor wind-speeds and lower humidity during hot weather decrease demand for air conditioning energy in Sydney, whereas low wind and high humidity are associated with the opposite effect.

All appliances exhibited stronger weather sensitivity in the summer than in the winter. For example the amount of day-to-day variance in reverse cycle air-conditioning energy consumption explained by outdoor weather fluctuations is 21% greater in the cooling season than in the heating season. Similarly domestic hot water systems were found to be up to 25% more weather sensitive during the summer.

A novel analytic technique known as Probit regression was used to model the relationship between binary response variables like appliance being switched on or off, and continuous predictor variables such as degree days. This method was used to determine the probability of space heating and cooling appliances being switched on under various outdoor weather conditions. In Sydney an 5.5°C degree-day (using an 18^{o}C base) during summer is likely to see 50% of all households owning refrigerated air-conditioning turn those appliances on at some stage throughout the day. In winter, a –7.2°C degree-day (again relative to a base of 18^{o}C) is likely to see half of all Sydney households owning reverse-cycle air-conditioners turn those appliances on for heating at some stage throughout the day. In the case of room heaters, 50% of households owning such appliances were likely to turn them on at some stage during a –7.0°C degree-day. These quantitative relationships, along with load profiles and the direct relationships produced between energy consumption and outdoor weather, have the potential to assist in the prediction of grid-wide system spikes and peaks.

The statistical dependencies observed between appliance energy consumption and outdoor weather were applied to observed long-term and simulated greenhouse climatological data for Sydney (obtained from the Australian CSIRO’s Limited Area Model - DARLAM), in order to estimate the impacts of a greenhouse climate change. The magnitude of greenhouse climatic impacts depended on the nature of the appliance; cooling devices experienced an increase in energy consumption (31% for space cooling), whereas heating devices experienced a decrease in energy consumption (19% for space heating). The implications of this regional-scale climatic impacts assessment provide further impetus for energy policy and technology adaptation to and mitigation of global climate change.

1 INTRODUCTION

1.1 Residential Energy Study

Pacific Power in conjunction with Sydney Electricity carried out a Residential Energy Study (RES) in New South Wales during 1993-1994 (Camilleri *et al.*, 2000). The study involved directly metering the energy end-use of household appliances in a sample of about 289 houses across NSW. Pacific Power has used the data in their residential end-use forecasting model and for short-term load forecasts, particularly with respect to system peak demands. A further study on the same database commissioned by the Australian Greenhouse Office (AGO) examined the patterns of usage and energy consumption of the appliances (Camilleri *et al.*, 2000). Figure 1.1 details the household share of energy consumption by end-use for the RES data. The study found, *inter alia*, significant summer and winter peaks in energy consumed by many of the appliances. The top three end-uses in Figure 1.1, which are collectively responsible for 77% of the total energy consumption (domestic hot water, refrigeration/freezing and space heating/cooling) demonstrated climatic sensitivity in the RES study.

This report examines this weather/climate sensitivity for a selection of the household appliances monitored in RES houses within the Sydney region. The data collected during the RES will be analysed in conjunction with weather data from the same study period. Statistical relationships deduced between outdoor weather and individual appliance energy consumption for the 18-month sample will define the quantitative climate sensitivity of appliance energy consumption. These sensitivities will then be applied to long-term climatological observations (1961-1990) and future greenhouse climate scenario predictions (2031-2060). These analyses will provide the basis for discussion of the potential impacts of climate change on household appliance energy end-use in the Sydney region.

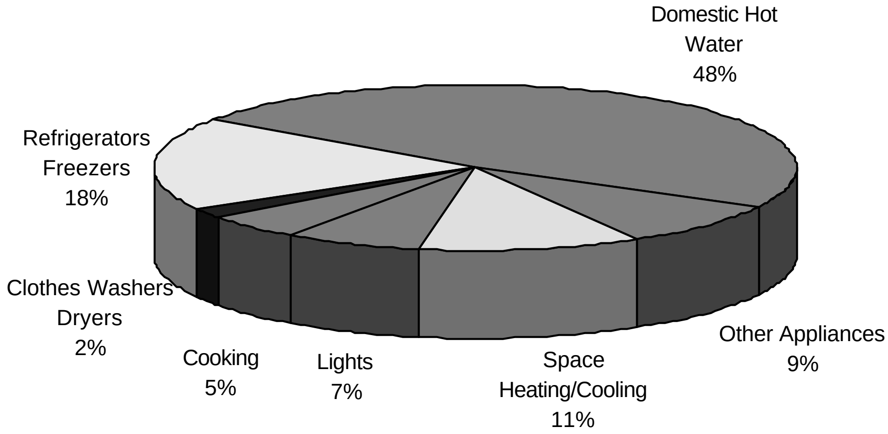


Figure 1.1 Household energy consumption by end-use for NSW 1993/94. Data from the RES (Camilleri *et al.* 2000).

1.2 Weather Sensitivity

In most electricity systems the residential sector is one of the main contributors to system peak (Bartels and Fiebig, 1996). In particular household space heating and cooling appliances have a large effect on electricity peak loads.

Many household appliances' usage patterns are expected *a priori* to be affected by outdoor weather. For example, we choose to artificially heat and cool our houses in order to minimise the effects of extreme outdoor temperatures and create a more comfortable indoor living environment. Figure 1.2a details the link between space heating/cooling appliances and the outdoor environment. Energy consumption will depend on the nature of the building envelope (e.g. materials, air-tightness); heat will be lost and gained depending on levels of insulation and ventilation (CSIRO, 2001). Occupant behaviour, such as individual levels of thermal comfort and hours of occupancy will also affect energy consumption. Some household appliances contain thermostats; for example domestic hot water systems and refrigerators. The energy consumption of these appliances can be expected to depend on the surrounding indoor temperatures and also rates of heat exchange between the appliance in question and its microenvironment. Figure 1.2b details the link between refrigeration, indoor hot-water systems, and the outdoor atmospheric environment. Once again the nature of the building envelope will affect the level of heat exchange between the indoor and outdoor environment. Occupant behaviour, such as refrigerator door openings and the number of occupants showering will also affect energy consumption. The level of heat exchange between these appliances and the indoor environment could also be affected by the HVAC system (heating, ventilation and air-conditioning). In all these examples, a more detailed understanding of the complex relationship between outdoor weather, appliance usage and energy consumption will enable power utilities to manage peak loads more effectively.

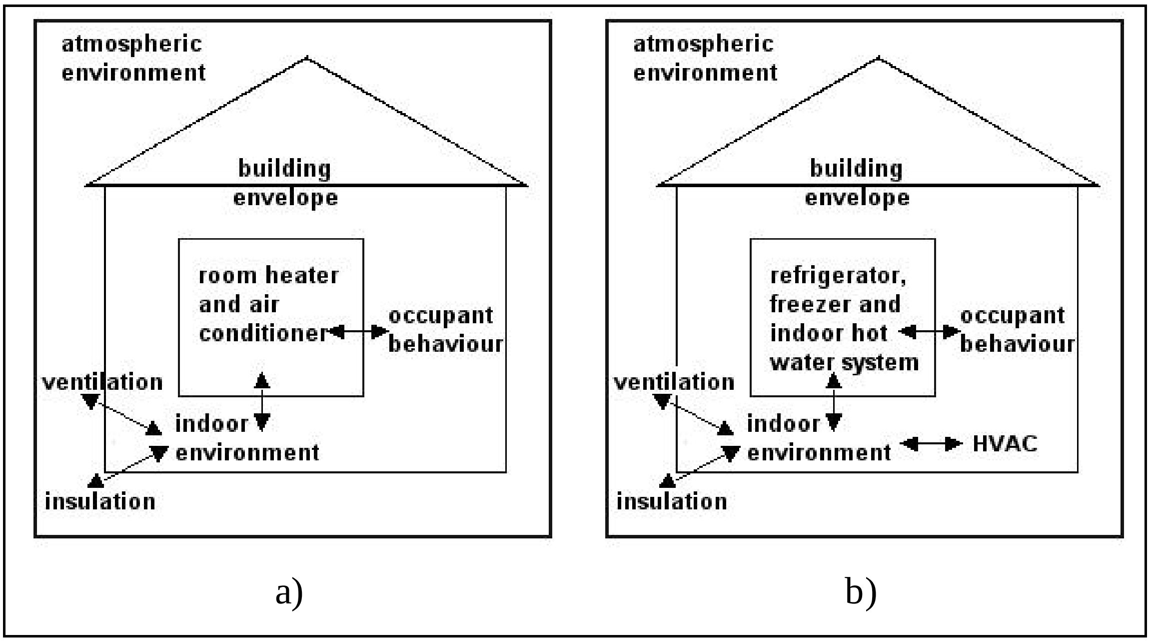


Figure 1.2 The link between the outdoor environment and household appliance energy consumption for a) space heating and cooling appliances and b) refrigeration, freezers and indoor hot water systems. Arrows indicate heat exchange.

1.3 Climate Change and Household Energy

The Intergovernmental Panel on Climate Change (IPCC) reports that global average surface temperature is projected to rise by 1.4-5.8°C by 2100, relative to 1990 (Cubasch *et al.*, 2001). In order to manage this projected rise the United Nations Climate Change Conference in Kyoto, 1997, set in place the Kyoto Protocol in which some developed nations agreed to limit their greenhouse gas emissions, relative to the levels emitted in 1990. Australia's requirement within the Kyoto Protocol is to limit growth of its greenhouse emissions to 8% above 1990 levels by 2008-2012 (AGO, 2000). This represents a 30% reduction compared to the expected growth in emissions under a "business as usual scenario". The residential sector contributes 17% of Australia's greenhouse gas emissions (AGO, 2001). Emissions in Australia are projected to rise by 1.8% per year, under a “business as usual scenario”, largely driven by high emissions growth in the electricity sector, which in Australia is highly dependant on coal, the most emissions-intensive fuel (Pascoe, 2001).

The energy sector has shown that it is capable of effectively responding to climate change policies, as shown by the introduction of Minimum Energy Performance Standards (MEPS) in Australia. MEPS have been successful in eliminating less efficient models from the market, for appliances such as refrigerators, freezers and domestic electric hot water storage units. Energy efficiency programs such as star rating energy labels have also had an impact by relaying to consumers comparative information about the energy efficiency of new appliances including refrigerators, freezers and air-conditioners (Wilkenfeld, 1993).

The energy consumption of weather sensitive appliances is also affected by the performance of the building shell in which they are installed. Highly efficient building shells can greatly reduce heating requirements and even eliminate the need for artificial cooling, thus reducing overall energy consumption. To assist consumers in this respect the thermal performance of individual household building shells can now be assessed with the introduction of the Nationwide House Energy Rating Software (NatHERS) (CSIRO, 2001). However, for changes in technology and policy to occur, the impact of climate change on energy consumption under a “business as usual scenario” needs to be fully appreciated. The statistical relationship between energy consumption and outdoor weather to be deduced in this study can be used to predict the impact of climate change on appliance energy consumption. These projections can then provide the necessary impetus for implementing changes in policy and technology to further reduce the levels of greenhouse gas emission attributable to household appliances. Energy efficient appliances have the potential to significantly reduce energy-related greenhouse gas emissions in Australia (AGO, 2001). However, it needs to be appreciated that improved building shell performance can effectively reduce the nexus between weather and household energy consumption for appliances studied in this report. No data on building shells was available with the appliance end-use data, so it is not possible to draw any firm conclusions regarding the impact of building shell performance and occupancy on appliance energy consumption from this analysis.

1.4 Literature Review

The following Section presents a review of previous studies into the effects of weather and climate change on household appliance energy consumption.

1.4.1 Appliance Energy and Weather

Previous studies have tended to focus on either total household energy consumption or heating and cooling energy consumption patterns. A study in Canada by Ugursal and Fung (1996) analysed the impacts of appliance efficiency and fuel substitution on residential end-use energy consumption. However, instead of directly measuring appliance electricity usage, Ugursal and Fung relied mainly on simulation studies. A similar Residential Energy Consumption Survey (RECS, 1997) by the USA Department of Energy (DOE) gathered consumption surveys directly from end-users along with information on the energy related characteristics of households. Previous studies have also looked at broad climatic zones (RECS, 1997; Pacific Gas and Electricity Company, 1994) or used climatological normals (Sailor and Munoz, 1997) from historical weather data, rather than concurrent weather observations.

In a similar monitoring program to Pacific Power's RES in NSW, the Household Energy End-Use Project (HEEP) in New Zealand directly monitored individual appliances in 130 households. The analysis included building and socio-demographic characteristics of the households (Isaacs, 1997). However, emphasis in the analysis and discussion was placed on individual appliances' energy consumption in relation to indoor, rather than outdoor temperature.

A domestic electrical end-use measurement campaign undertaken in France (Sidler, 1997) over twelve months in 1994/95, involved monitoring eight appliances (with 10 minute readings) in 94 households for one month each. Appliance energy consumption was compared by season, winter and summer, but did not include concurrent weather observations. Each household was only monitored for one month, so comparisons of individual appliance energy consumption could not be made on either synoptic or seasonal timescales. The study did not include electrical space heating and cooling nor domestic hot water appliances.

More recent end-use campaigns in Europe have involved discovering potential reductions in energy consumption when currently installed household appliances are replaced with the most energy efficient ones available on the European market. The French ECODROME project monitored appliance electricity consumption in 20 household over two years (Sidler, 1998). All existing plug loads and the electric light circuit were monitored for the first year, at the beginning of the second year all appliances and light bulbs were replaced by the most efficient alternatives available on the European market. Results indicated that the average annual energy saving per house from the use of efficient equipment is 1800kWh/year. A more recent project, EURECO, followed a similar methodology and approach to ECODROME, however rather than replacing individual appliances, the measured consumption of currently installed appliances was compared to that of the most energy efficient model of similar capacity and function (Sidler *et al.,* 2002). Appliances were monitored in 100 households in each of Denmark, Italy, Portugal and Greece with ten-minute intervals over one month. Based on analysis for all four countries, annual savings were calculated to vary from 1000-1200kWh/year (space heating, water heating and cooking appliances were not included).

The present study is the first study of its kind in Australia where directly monitored energy consumption is analysed alongside concurrent weather observations. Awareness of the weather sensitivity in energy end-use can provide more information on actual in-use energy consumption in comparison to laboratory measurements for domestic appliances. Apart from providing a rational basis for climatic impact studies this knowledge may also provide practical benefits in relation to the implementation of testing procedures for MEPS and Energy Star labels.

1.4.2 Appliance Energy and Climate Change

Previous studies on climate change and appliance energy consumption have shown the impacts to be location specific, depending on the amount of energy use related to heating compared to cooling. Space heating and cooling of buildings has generally assumed to be one of the most climate sensitive end-uses of energy (Scott *et al.*, 2001; Skea, 1997).

Rosenthal *et al.* (1995) estimated the impact of global warming on US energy expenditures for space heating and cooling in residential and commercial buildings. Average results from six General Circulation Models (GCMs) of the global climate system were used to estimate change in heating and cooling degree-days in five US climate zones after a 1°C global warming. Change in energy consumption was estimated using the assumption that degree-days are approximately proportional to space conditioning energy requirements. Results indicated a nationwide increase of cooling season energy consumption of 20%, a decrease of heating season energy consumption of 6%, with an overall net decrease in annual energy consumption of 11% across the USA. The study also took into account regional differences in population and baseline space conditioning intensity levels and market penetration rates across regions.

1.5 Aims of the Current Project

The aims of the following analyses are to:

1) Quantify the dependence of residential appliance energy consumption on the outdoor atmospheric environment in Sydney.

2) Define the most appropriate thermal climate index affecting energy consumption for space heating and cooling.

3) Analyse appliance usage thresholds and whether they hold true to the current heating and cooling degree-day base temperatures.

4) Project future appliance energy end-use by applying empirically derived weather sensitivity factors to greenhouse climate scenarios for the Sydney region.

2 DATA RESOURCES

2.1 Residential Appliance Energy End-Use Data

The appliance energy end-use data came from the Residential Energy Study (RES) introduced in Section 1.1. The project involved directly monitoring a range of household appliance types (14 in total) with half hourly data collection in 289 households in New South Wales (NSW) and the Australian Capital Territory (ACT). A total of approximately 1700 appliances were monitored. The earliest monitoring commenced on 18 March 1993; all monitoring was completed by 7 October 1994.

2.1.1 The Setting (Sydney and NSW)

Houses selected for the RES were located mainly in Sydney but some were in Canberra and country NSW. Due to difficulties and expense of acquiring quality-controlled Automatic Weather Station data for the monitoring period in question, only houses within the Sydney region have been used in the following analyses. Half-hourly weather data for the monitoring period was available for Sydney Airport and Bankstown Airport Automatic Weather Stations (AWS). The Sydney region was split into two broad zones found to be climatically homogeneous, and well represented by the two automatic weather stations selected for the analysis. A study of Sydney's mean maximum and minimum monthly temperatures from a Climatic Survey of Sydney (Bureau of Meteorology, 1991) guided the delineation of the climatic zones (see Figure 2.1). Individual households were located by their postcodes; the relatively small area of postcode districts in Sydney made this an adequately accurate method for the purposes of this project. Sixty-three households were located within the Sydney Airport AWS climatic zone and 73 within Bankstown Airport's, giving a total of 136 households.

2.1.2 Original Format of Energy End-Use Data

For most households in Pacific Power's data collection, eight channel data loggers were used with the last channel used to monitor total household load. Up to seven load profiles (half-hourly energy readings) for individual appliances were recorded within each household. The original RES sample was stratified on the basis of the household total electricity use, and therefore was not designed to take into account the use of other fuel types.

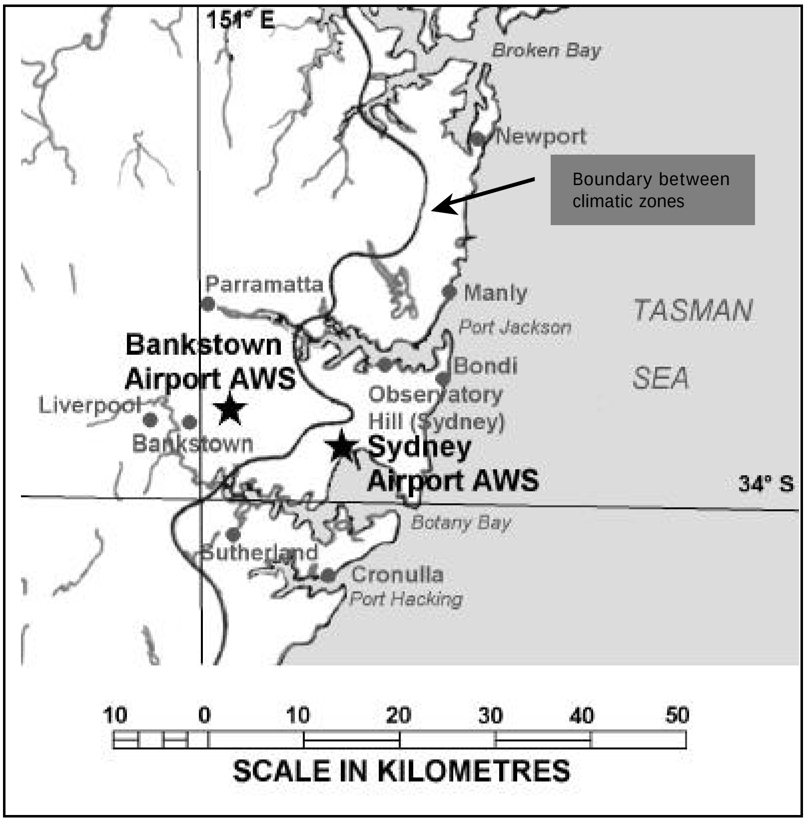


Figure 2.1 Location map of households under analysis; Sydney's area was split into two climatologically homogeneous zones. Households located to the east of the boundary were associated with the Sydney Airport AWS, households located to the west of the boundary were represented by Bankstown Airport AWS.

The duration of data time-series for each household ranged from a few days up to the entire monitoring period of 18 months. Of the appliances monitored only 8% had complete records without any apparent errors or missing half-hourly readings. Of the total 289 households monitored in the RES sample, 129 were all electric while the others had at least one gas appliance (Camilleri *et al.*, 2000).

Fourteen different appliance types were monitored in all: air-conditioners, domestic hot water, dishwashers, dryers, freezers, refrigerators, electric heaters, lights, microwaves, pool pumps, cooking ranges, televisions, washing machines and waterbeds. From these, air-conditioners, room heaters, refrigerators, freezers and domestic hot water were selected for detailed weather sensitivity analysis in this report. The appliances chosen were those involved in household space heating and cooling and appliances containing temperature regulators, such as thermostats (refer to Figure 1.2).

2.2 Bureau of Meteorology Weather Data

2.2.1 AWS Data

Weather data were purchased from the Australian Bureau of Meteorology for Sydney and Bankstown AWSs. Half-hourly observations for the following weather variables: temperature, rainfall, wind speed and relative humidity, were requisitioned for the entire 18-month period of the RES study. These data were used in the empirical definition of appliances energy weather sensitivity models.

2.2.2 Long-term Climate Data

Long-term meteorological records were also obtained for the Sydney Airport and Bankstown Airport AWSs for use as a baseline (current climate), against which the effects of a greenhouse climate scenario on household appliance energy consumption could be compared. Thirty years of three-hourly temperature data were requisitioned for both weather stations. From these data an average monthly degree-day index value for Sydney was calculated. The baseline chosen in this study is the 30-year "normal" period as defined by the World Meteorological Organisation (WMO, 2001). The current WMO normal period is 1961-1990. The period ends in 1990, which is the common reference year used for climatic and non-climatic projections by the IPCC in the First, Second and Third Assessment Reports (IPCC-TGCIA, 1999; Scott *et al.*, 2001). It represents the recent climate to which present day energy consumption usage is assumed to be fully equilibrated.

2.3 Greenhouse Climate Scenarios

To select the most appropriate climate model for greenhouse climate scenario impacts research, output from four General Circulation Models (GCM) and one Limited Area Model (LAM) were compared to see which produced the most accurate representation of present day climate. One of the criteria commonly used in construction of regional climate scenarios for impact assessment is the skill with which the Climate Model simulates present day climate in the region. The widely accepted assumption is that if a model simulates the present day climate accurately it stands a reasonable chance of accurately representing future climate (IPCC-TGCIA, 1999). While this assumption may be questioned we also have to recognise that these models currently represent the best available option.

Climate scenarios are representations of future climate that are consistent with our understanding of the effects of increased greenhouse gas concentrations on the global climate system and assumptions about future emissions of greenhouse gases. The IS92a scenario was chosen for this impacts study because it has been widely adopted as a standard reference scenario for use across a variety of impacts assessments (IPCC-TGCIA, 1999). This scenario involved climate models modelling historical forcing due to greenhouse gases, thus enabling comparisons between modelled and observed climate. IS92a climate simulations also extend into the future under a scenario of future atmospheric composition. For IS92a there is an assumed forcing of 1% increase per year in equivalent CO_2 concentration (Legget *et al.*, 1992).

2.3.1 IPCC Climate Data Centre

Climate data were acquired from four different General Circulation Models from the IPCC's Data Distribution Centre (IPCC, 2001):

- The German Climate Research Centre (ECHAM4)
- The UK Hadley Centre for Climate Prediction and Research (HadCM2)
- The Canadian Centre for Climate Modelling and Analysis (CGCM1)
- The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) coupled ocean-atmosphere GCM

2.3.2 CSIRO DARLAM - Climate Model Data

It is widely agreed that General Circulation Models do not have spatial resolution that is fine enough to simulate climate and climate change on a regional scale (e.g. Hennessy *et al.*, 1998; Smith and Pitts, 1997). In response to this shortcoming the Australian CSIRO's Division of Atmospheric Research (DAR) has produced a Limited Area Model (DARLAM). DARLAM is a regional climate model that has produced high-resolution climate change scenarios over NSW. The DARLAM experiment uses 140 years of input data from 1961-2100 from the CSIRO coupled ocean-atmosphere GCM. The experiment involved DARLAM first being nested in the GCM using a horizontal resolution of 125km over Australasia and the south Pacific. This provided fine resolution boundary conditions for a second nesting over south-eastern Australia at 60km resolution (Hennessy *et al.*, 1998; Whetton *et al.*, 2001). Data from the GCM provides boundary conditions for the LAM (Hennessy, 1998). The finer spatial and temporal resolution of LAMs enable more detailed representation of orography and coastlines than GCMs and as a result, are widely assumed to provide a more realistic representation of climate at regional scales than GCMs.

2.3.3 Model Selection Procedure

DARLAM was selected for closer analysis in the present impacts assessments mainly due to its high spatial and temporal resolution. The double nesting of the LAM within CSIRO's GCM has produced climate change data at a spatial resolution of 60km by 60km over NSW, this is a much higher resolution than the GCMs. Without the nesting of the LAM the CSIRO CGM has a grid size of 600km × 350km, which severely limits its ability to reproduce current climate for the Sydney region. However, the GCM has produced levels of global warming within the range deemed acceptable by the IPCC (Houghton *et al.*, 1996), establishing it as a suitable host for DARLAM.

DARLAM is also attractive to the present project due to its finer temporal resolution of temperature data. For the impacts assessment of appliance energy consumption a monthly average degree-day is required. DARLAM outputs three-hourly temperature data for Sydney compared to just daily maxima and minima from the GCMs. The relationship between observed monthly degree-days and DARLAM's simulated monthly degree-days produces a high R^2 of 0.97 indicating an excellent representation of current climate for Sydney.

2.3.4 Scenario Calibration and the Delta-T Method

To ascertain the change in climate during a greenhouse climate scenario in Sydney, average monthly degree-days were calculated from DARLAM greenhouse climate scenario output for the period 2031-2060. The change in monthly degree-days between DARLAM's current and greenhouse climates was then applied to the monthly degree-days for Sydney actually observed during years 1961-1990. A scenario for future climate was obtained by adjusting the baseline observations by the difference between period-averaged results for the model experiment and the corresponding averages for the model control simulation (the Delta-T method) (IPCC-TGCIA, 1999). The change in climate equates to an overall increase in mean temperature of 1.4°C.

3 METHODS

3.1 Degree-Day Methods

Half-hourly outdoor temperature data from each weather station were used to calculate degree-days for each day of the study period: 18/03/1993 - 7/10/1994. Degree-days and, on a finer temporal scale, degree hours, are universally used in the heating, ventilation, air-conditioning (HVAC) industry to relate outdoor air temperature to energy consumption. A degree-day is a unit for measuring the extent to which outdoor average temperature falls below, in the case of heating, or above, in the case of cooling, an assumed base temperature. The base temperature of 18°C used in the current project has been used by others for some research in Australia (Badescu and Zamfir, 1999). There has, however, been some controversy as to the correct base temperature in this country. A common approach in the energy sector has been to use 18°C for heating degree-days and 24°C for cooling degree-days (Harrington, 2001b). These base temperatures presume that there is negligible energy consumed for domestic heating or cooling purposes between mean daily temperatures of 18°C and 24°C. An empirical resolution of the issue would be to observe the mean daily temperature associated with minimum heating and/or cooling energy consumption, but to-date there has been no such analysis in Australia. Degree-days are commonly used in the HVAC industry to estimate energy consumption (e.g. El-Shaarawi and Al-Masri, 1996). As energy consumption was a known variable in this study it can logically be used to determine the most appropriate degree-day base temperature for Sydney.

Degree-days are commonly calculated by measuring the extent the average of the daily maximum and minimum temperatures fall above or below the base temperature (Badescu and Zamfir, 1999). If diurnal temperature symmetry does not prevail then over or underestimations of the true degree-day value occurs. In this study degree-days were calculated from “degree half-hours”. These degree half-hours were then averaged to obtain a degree-day, as summarised in Equation 3.1.

Since the same base temperature of 18°C is used in summer and winter throughout this report, a negative degree-day represents a heating degree-day and a positive degree-day, a cooling degree-day. This sign convention centred on 18°C has the advantage of allowing heating and cooling season results to be plotted on the same graph.

A base temperature of 18°C was used in the following calculation.

$$degree\ \ days = \frac{1}{48}\sum_{i=1}^{48}(degree\, half\ \ hours)_i \qquad \text{(eq. 3.1)}$$

where (degree half-hours)$_i$ = T_{out_i} - 18°C, i = 1,2,…,48, and where T_{out_i} is the average ith half-hourly outdoor temperature in degrees celsius.

3.2 Thermal Comfort Indices

Degree-days and degree half-hours were also calculated using composite thermal comfort indices, namely Standard Effective Temperature (SET) and Effective Temperature (ET*). SET and ET* are indices used widely in the heating and air-conditioning industry to combine the effects of temperature, thermal radiation, humidity, wind speed, clothing insulation and metabolic rate on human thermal comfort (Gagge *et al.*, 1986). ET* primarily takes into account the effects of air temperature, thermal radiation and humidity on human thermal comfort with all other variables in the comfort equation set as constants. SET extends the index to include the effects of clothing insulation, metabolic rate and wind. In the present study wind speed measurements were scaled down from the 10m anemometer height to that which would experienced by people on the ground using the Power Law (Aynsley *et al.*, 1977).

Compared to more conventional air temperature degree-days these more sophisticated thermal comfort indices can be expected to improve statistical associations with HVAC heating and cooling energy. For example, the presence of a sea breeze on a warm day may offset the discomfort normally expected on a high degree-day, and therefore air-conditioner usage may be lower than expected based on air temperature alone. Using a composite index like SET takes these mitigating circumstances into account, by rationally translating the effects of elevated air speed, or depressed humidity into their temperature equivalents. There are numerous versions of the ET* and SET indices in the public domain, but the software published by Fountain and Huizenga (1996) was selected for this study because its development was directly funded by the American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc. (ASHRAE), and as such, represents a *de facto* industry standard.

3.3 Statistical Methods

Apart from standard correlation and regression techniques, the main specialist statistical tool used in this report is known as Probit regression (SAS Institute, 1999).

Probit regression was used in an analysis of heating and cooling appliances to assess the relationship between degree-days (in a few cases mean hourly temperature) and the probability of the appliance being switched on. Binary response variables are those possessing just two states. In the present study there were several appliances that were binary - having "on" and "off" states. At what temperature thresholds do people tend to heat or cool their houses? The response variable was recoded with the value of either “1” (if the appliance was switched on at any time during the day, or hour) or “0” (if the appliance remained switched off) for the entire day. After binning the on/off responses of all households possessing the appliance according to outdoor degree-day values, the probit technique fitted maximum likelihood sigmoidal models to the "on" probabilities in each degree-day bin (bin widths of 0.5°C degree-days were used). In this case the probabilities represent the percentage of appliances, across the entire sample of households owning such an appliance, being switched on. The “goodness of fit” (*sic*) of the probit model is tested with a Chi-square statistic, where a low Chi-square and a high *P*-value (i.e. close to unity), indicate no significant difference between the probit model’s predicted results and those actually observed. A statistically significant chi-square “goodness of fit” test (i.e. low *P*-value) prompts the probit model to compensate by widening its 95% fiducial limits (like confidence intervals in normal regression). A good fit between the probit model and data (a low Chi-square and a high *P*-value) defaults to a *t*-value of 1.96 in the calculation of 95% fiducial limits, but this *t*-value is increased whenever the Chi square test reaches significance (SAS Institute, 1999).

Probit analysis fits a cumulative normal frequency distribution curve (i.e. a logistic "S-shaped" function or ogive). The curve shows the percentage of people who would change their appliances from "off" to "on" for each successive degree-day bin. The degree-day value at which the maximum number of people changes their appliance from "off" to "on" is defined here as the threshold temperature. This threshold temperature occurs at 50% on the probit axis (Y) and the corresponding X-axis value can be interpreted as the temperature (or degree-day value) at which half the sample had their appliance switched on for at least some of the day while the other half had them switched off all day. This threshold temperature can be seen as the temperature stimulus at which the majority of people make their decision to heat or cool their houses (Ballantyne *et al.*, 1977).

4 RESULTS

Results are presented in two main sections dealing with weather sensitivity and climatic impacts. Within each section the results are organised by appliance type.

4.1 Appliance Energy End-Use Weather Sensitivity

4.1.1 HVAC

Thirty-two percent of NSW households currently own air-conditioners, either reverse cycle or cooling only. Most households have some type of space heating device with 42% having electric room heaters (22% of households have gas heating, 15% wood and 4% oil heaters) (AGO, 1999).

Households with air-conditioners

Daily average energy consumption and the average hours per day air-conditioners were switched on were calculated across all houses within each of the two Sydney climatic zones, for each of the 48 half-hourly readings. Sample wide averages for energy consumption (Wh/day) and duration of appliance usage (hrs) were modelled in relation to degree-days and thermal comfort indices SET degree-days and ET* degree-days.

Figure 4.1 details the relationship between degree-days and energy consumption over the entire study period, split by season. The relationship is stronger in the cooling season (Figure 4.1c) with 56% of the variance in day-to-day energy consumption being explained by degree-days, compared to only 35% of energy consumption being related to degree-days in the heating season (Figure 4.1b). Energy consumption also tends to rise faster with an increase in degree-days in the cooling season than in the heating season.

The regression analysis of both heating and cooling season energy consumption in Figure 4.1a produced a parabolic equation. With a turning point at -0.25°C degree-days (the point at which the derivative of the function is zero). This point shows the degree-day value when neither heating nor cooling is required, or when they are least in demand.

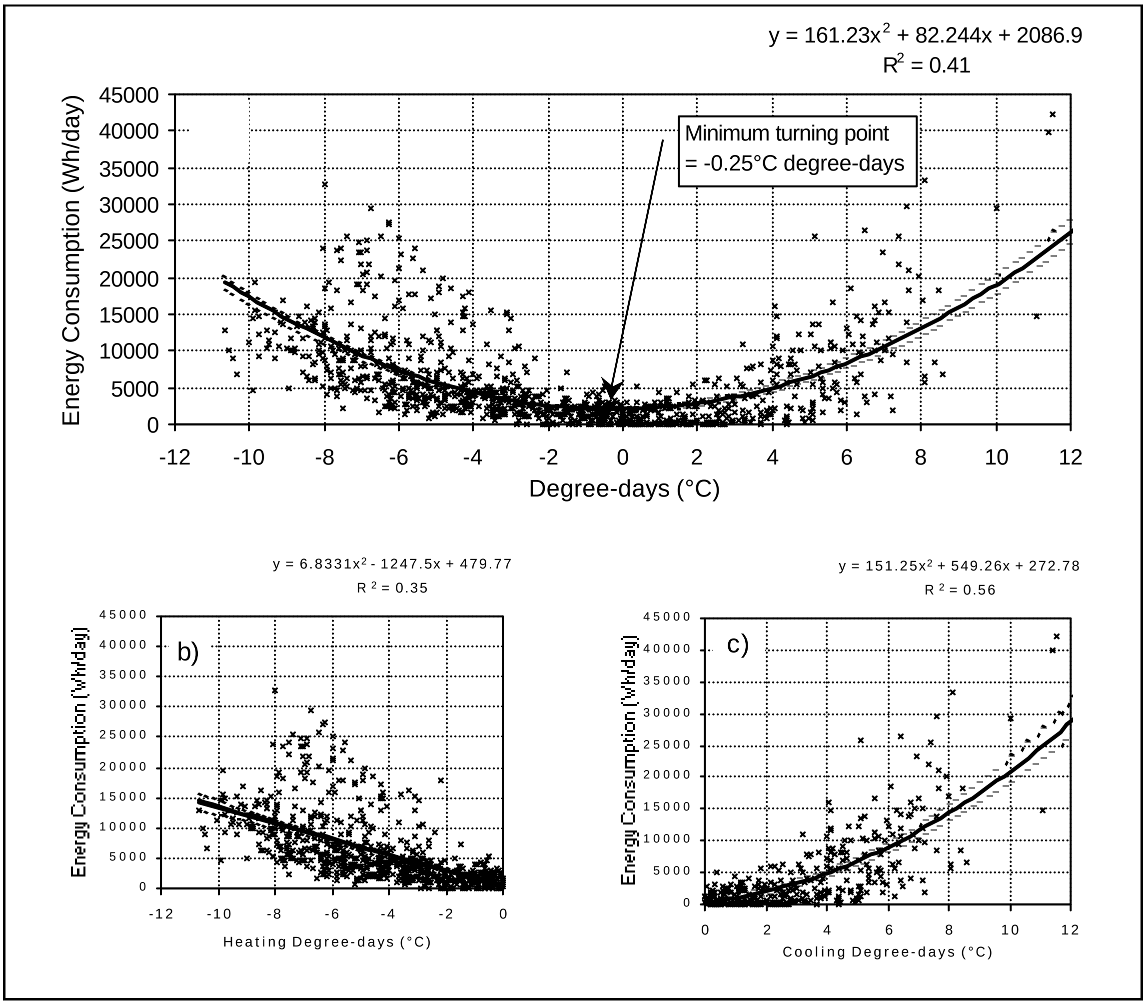


Figure 4.1 The relationship between air-conditioner average daily energy consumption in Watt-hours per day on the y-axis and degree-days on the x-axis for a) the entire year, b) the heating season and c) the cooling season. Regression models (solid curves) and 95% confidence intervals (dashed curves) were fitted with 2nd-order polynomials. Energy consumption was averaged over 47 households in the cooling season and 41 in the heating season.

The SET thermal climate index combines the comfort effects of temperature, relative humidity and wind speed into a single variable. The amount of day-to-day variance in air-conditioner energy consumption explained by SET degree-days was greater than with simple air temperature and ET* degree-days (combining the effect of temperature and relative humidity into one variable). Forty-five percent of the variance in air-conditioner energy consumption over both seasons can be explained by SET degree-days, compared to only 41% by degree-days and 39% by ET* degree-days. As with simple air temperature and ET* degree-days, the cooling season produces the stronger relationship between appliance energy consumption and SET degree-days (R^2=0.59).

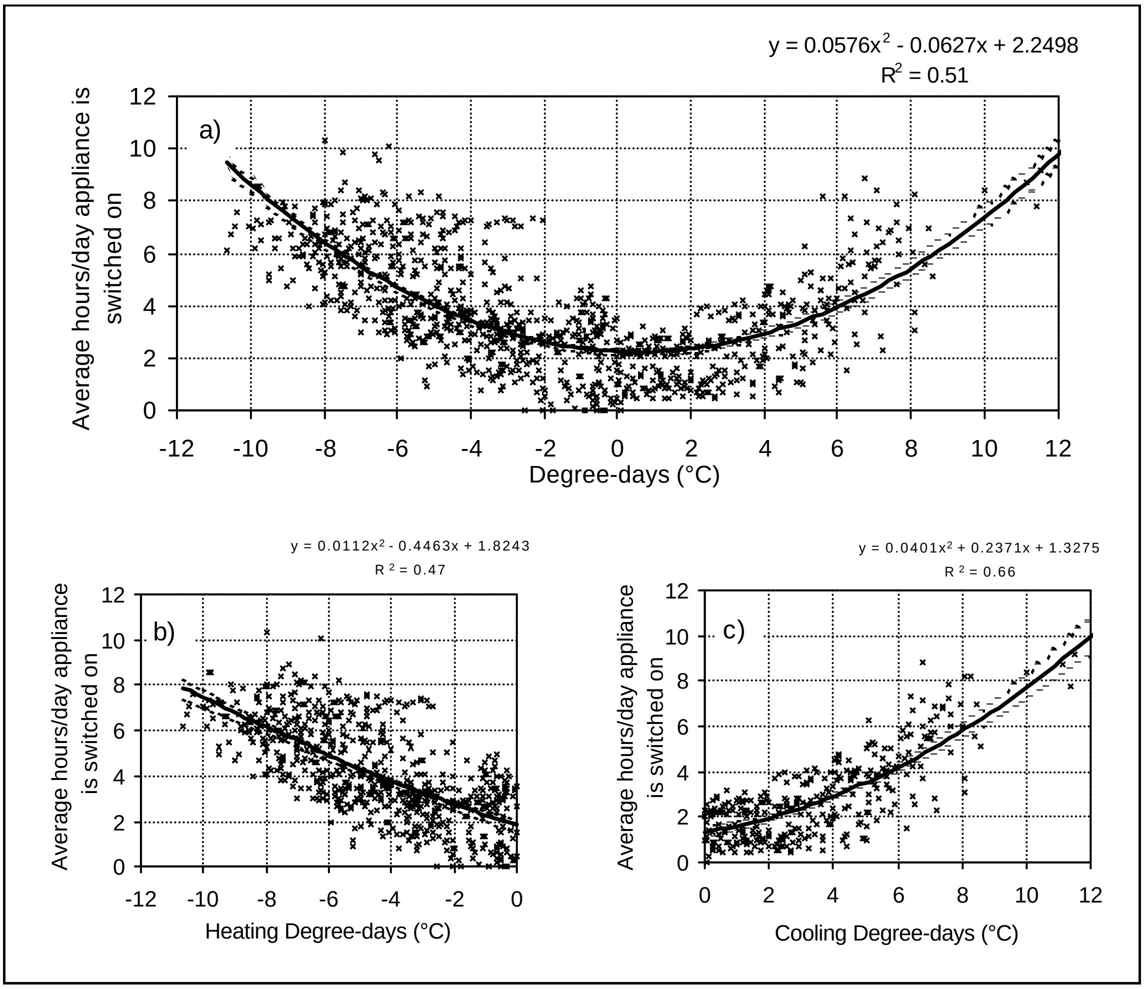
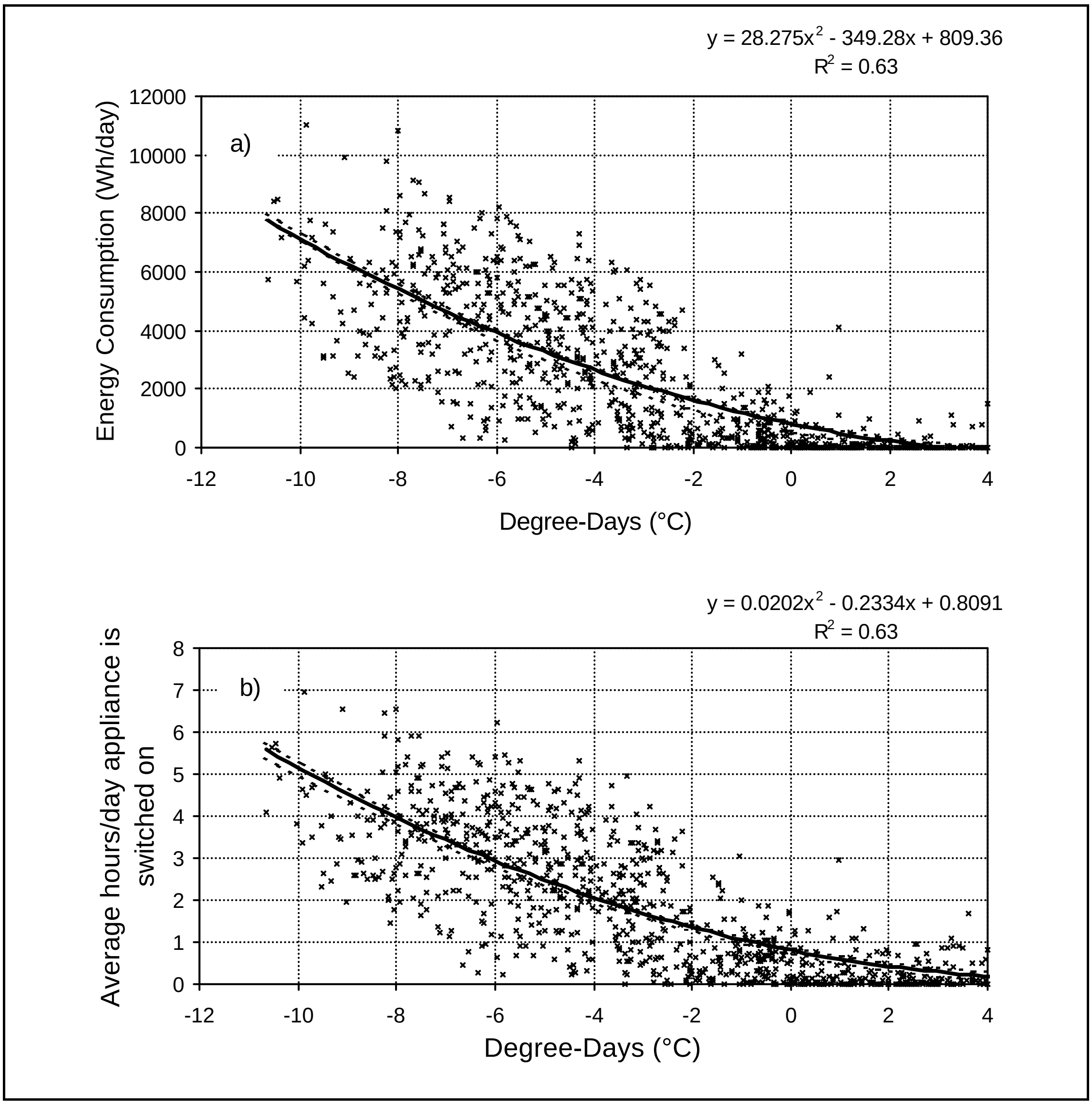


Figure 4.2 The relationship between average hours per day the air-conditioner is switched on, y-axis and degree-days, x-axis, for a) the entire year, b) the heating season and c) the cooling season. Hours per day the appliance is switched on is averaged over 47 households in the cooling season and 41 in the heating season. Each data point represents the average across all households regardless of whether the appliance was used or not, for each day.

The average hours per day appliances were switched on was more closely associated with degree-days than daily energy consumption. The amount of day-to-day variance in energy consumption accounted by the degree-day index was 41% (Figure 4.1) whereas the corresponding explained variance in appliance "switched on" hours was 51% (Figure 4.2). Again the cooling season produced a stronger relationship (R^2=0.66) than the heating season (R^2=0.47).

Households with electric heating

Room heaters are defined as portable electrical heating devices, usually only used to heat one section of a house. Common examples in Sydney are the oil column radiator, the bar radiator type and the fan-forced resistance heater type. Room heaters, unlike reverse cycle air-conditioners only have one mode (heating) and so analysis is confined to the heating season. Degree-days defined in terms of simple air temperature are a strong predictor of room heater energy consumption (Figure 4.3a) and the average number of hours per day the appliances are switched on (Figure 4.3b), with both analyses producing $R^2=0.63$. Room heater energy consumption begins to increase gradually with a decrease in degree-days below a value of +2.8°C degree-days.



Figures 4.3 a) average daily room heater energy consumption in Watt-hours per day, and b) the average hours per day the appliance was switched on, as functions of degree-days. Regression models (solid curve) and 95% confidence intervals (dashed curve) were fitted with 2nd-order polynomials. Seventy-one room heaters (i.e. households) were included in the analysis. Each data point represents the average across all households regardless of whether the appliance was used or not, for each day.

4.1.1.1 Probit Regression

Households with air-conditioners

Probit models indicate the probabilities of finding the air-conditioner (either in cooling or heating mode) in use as a function of degree-day values.

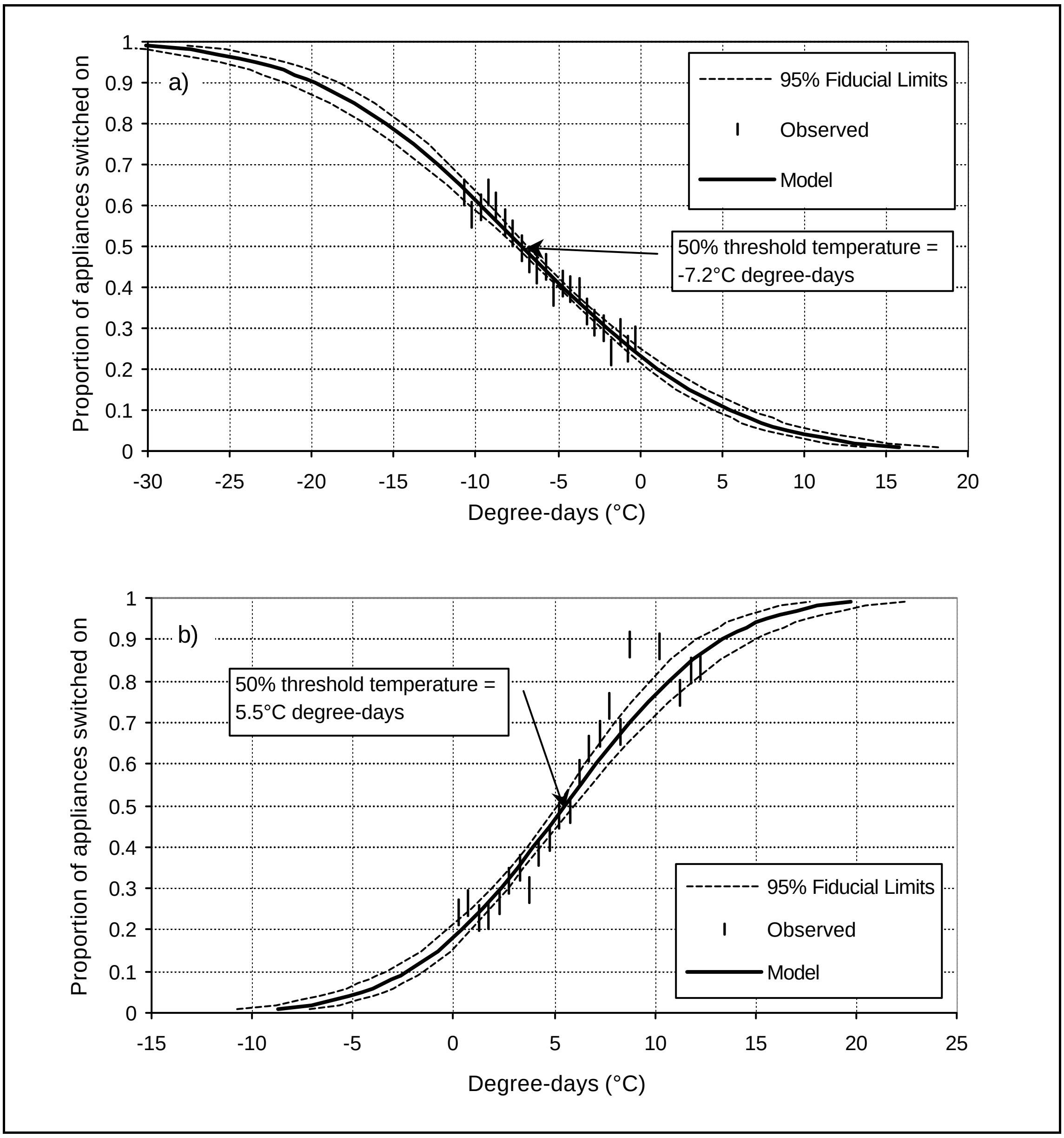


Figure 4.4 Air-conditioner probit regression results between a continuous explanatory variable (degree-days) and a binary response variable (whether or not the appliance was switched on at any time during the day). Analysis is split by a) heating season, and b) cooling season.

During the heating season probit regression between degree-days and the probability of appliances being switched on (Figure 4.4a) produced a small chi-square test statistic and therefore a large P-value ($\div^2$=15.5,df=20,P=0.8), indicating a good fit by the probit model. The probit model’s 50% threshold temperature was -7.2°C degree-days, with narrow fiducial limits (like confidence intervals in regular regression techniques) from -7.6°C to -6.8°C degree-days. This 50% threshold temperature is the point at which 50% of occupants had their appliance switched on at some stage during the day and 50% had it switched off all day. This is also the point at which the greatest number of households changed their decision from “off” to “on”.

Interestingly, on the coldest of Sydney days in the study period only 65% of households were observed to have their air-conditioners switched on to heat (Figure 4.4a).

Figure 4.4b shows the results of cooling season analysis in which the probit model produced a large chi-square test statistic and a low P-value ($\div^2$=34.2,df=20,P=0), indicating there was a statistical difference between observed data and the underlying probit model. The 50% threshold temperature for cooling season analysis was 5.5°C degree-days with 95% fiducial limits (between 5.1°C and 6.0°C degree-days). It should be noted that the fiducial (confidence) limits on the 50% threshold temperature were widened in recognition of the less-than-ideal goodness of fit test (a multiplier of 2.1, as opposed to 1.96 for good fits was used in the calculation of fiducial limits).

On the warmest days in the study period up to 90% of households were using their air-conditioner to cool. On a zero degree-day (i.e. mean daily temperature of 18^{o}C) 20% of households still had their air-conditioner switched on, the same level of usage occurred during the heating season; suggesting about 20% of households used their air-conditioners either in heating or cooling mode, all-year-round.

On extending the weather sensitivity analysis by using the ET* and SET thermal comfort indices during the cooling season, the probit regression model of air-conditioner usage and SET degree-days produced the best fit ($\div^2$=7.5,df=16,P=0.9). The 50% threshold temperature came in at 3.3°C SET degree-days with tightly defined 95% fiducial limits ranging from 3.0°C to 3.6°C SET degree-days.

Households with electric heating

Room heater probit analysis produced a significant difference between observed data and the probit model (÷^{2}=35.9,df=26,*P*=0). The 50% threshold temperature for room heaters was -7°C degree-days, with widened 95% fiducial limits (-8.1°C, -6.3°C degree-days), calculated using a *t*-value multiplier of 2.1 to compensate for the poor goodness of fit.

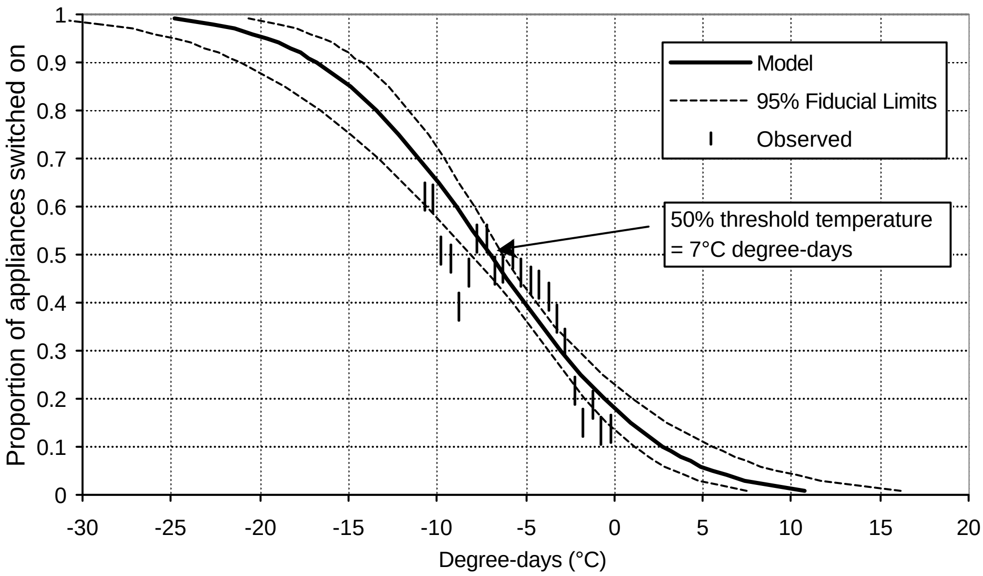


Figure 4.5 Room heater probit regression results between a continuous explanatory variable (degree-days) and binary response variable (whether or not the appliance was switched on at any time during the day).

Results similar to those from reverse cycle air-conditioners during the heating season (Figure 4.4a) suggest that, on the coldest of days observed during the entire study, only 63% of households had their electrical room heaters switched on (Figure 4.5).

4.1.1.2 Load Profiles

Households with air-conditioners

Load profiles were calculated for the air-conditioners in the Sydney sample in order to more closely examine the diurnal variability of energy consumption. Mean hourly energy consumption and concurrent air temperature observations were averaged across all households for each hour of the day. Due to the two modes of reverse cycle air-conditioners (heating and cooling) separate load profiles were produced for the heating and cooling seasons.

Figure 4.6 shows the diurnal distribution of air-conditioner energy consumption and corresponding outdoor air temperature for the heating and cooling seasons (a) and (b) respectively. Perhaps the most salient feature of the seasonal comparison in Figure 4.6is the mean daily energy peak in winter is twice that for summer. During the cooling season (Figure 4.6b) energy consumption begins to rise at 9am, peaking at 4pm and then rapidly decreasing to a minimum at 6am, closely tracking the diurnal temperature cycle. Assuming a causal link between temperature and energy consumption and extending it to the heating season we might expect the diurnal load profile to be a mirror image of the diurnal temperature cycle in that season, but the pattern of heating in Figure 4.6a does not follow diurnal temperature fluctuations so closely. Energy consumption has two peaks, one at 8am and the other at 9pm. During the heating season the daily minimum temperature occurs between 6-7am, but this does not coincide with the time of maximum heating energy consumption; in fact at this time of the day energy consumption is also at a minimum. Heating season load profiles for room heaters produced a similar twin-peak pattern to that of air conditioners during the heating season.

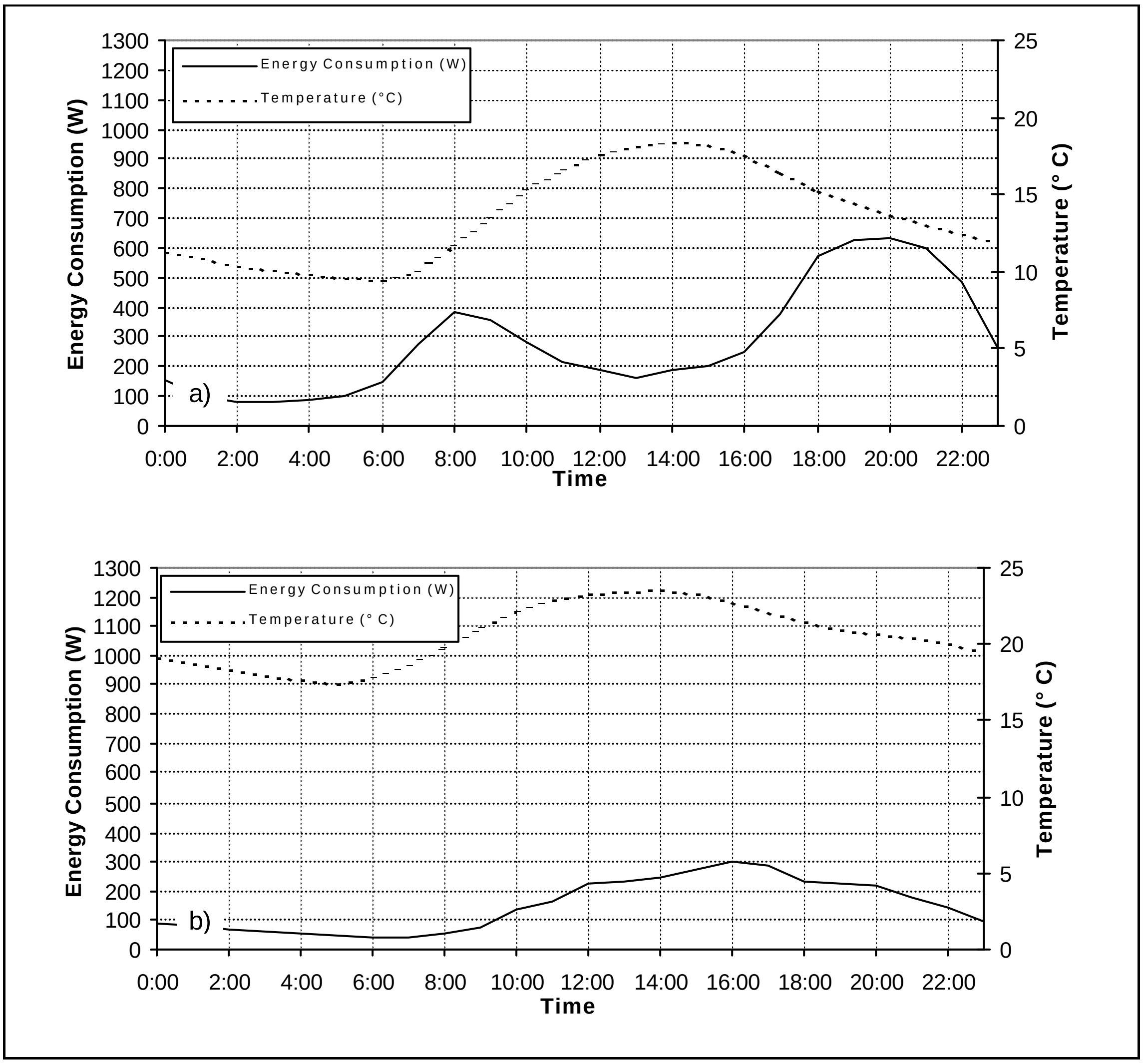


Figure 4.6 The diurnal distribution of mean hourly air-conditioner energy consumption and mean hourly outdoor temperature for a) the heating season, and b) the cooling season. Energy consumption is averaged across 47 appliances for the cooling season and 41 appliances for the heating season.

4.1.1.3 Single-Household Case-Study

The previous analyses involved aggregation across a sample of 47 air-conditioners in the cooling season and 41 during the heating season. As the large sample size can mask the intricacies of individual behaviour, the following section details analyses of an individual household. The household is located in western Sydney, approximately 20km away from the coast and therefore is covered by the AWS at Bankstown Airport (refer Section 2.1.1 for further information on the location of households and climate zones).

Hourly probit analysis of this single reverse cycle air-conditioner shows that usage during the cooling season conforms to the probit model quite closely (Figure 4.7b), although there was a significant difference between the observed data and the probit model (÷^{2}=143.9,df=19.*P*=0). The 50% threshold temperature was 27.1°C, and at this daily mean temperature the household in question had a 50:50 chance of having the cooler on.

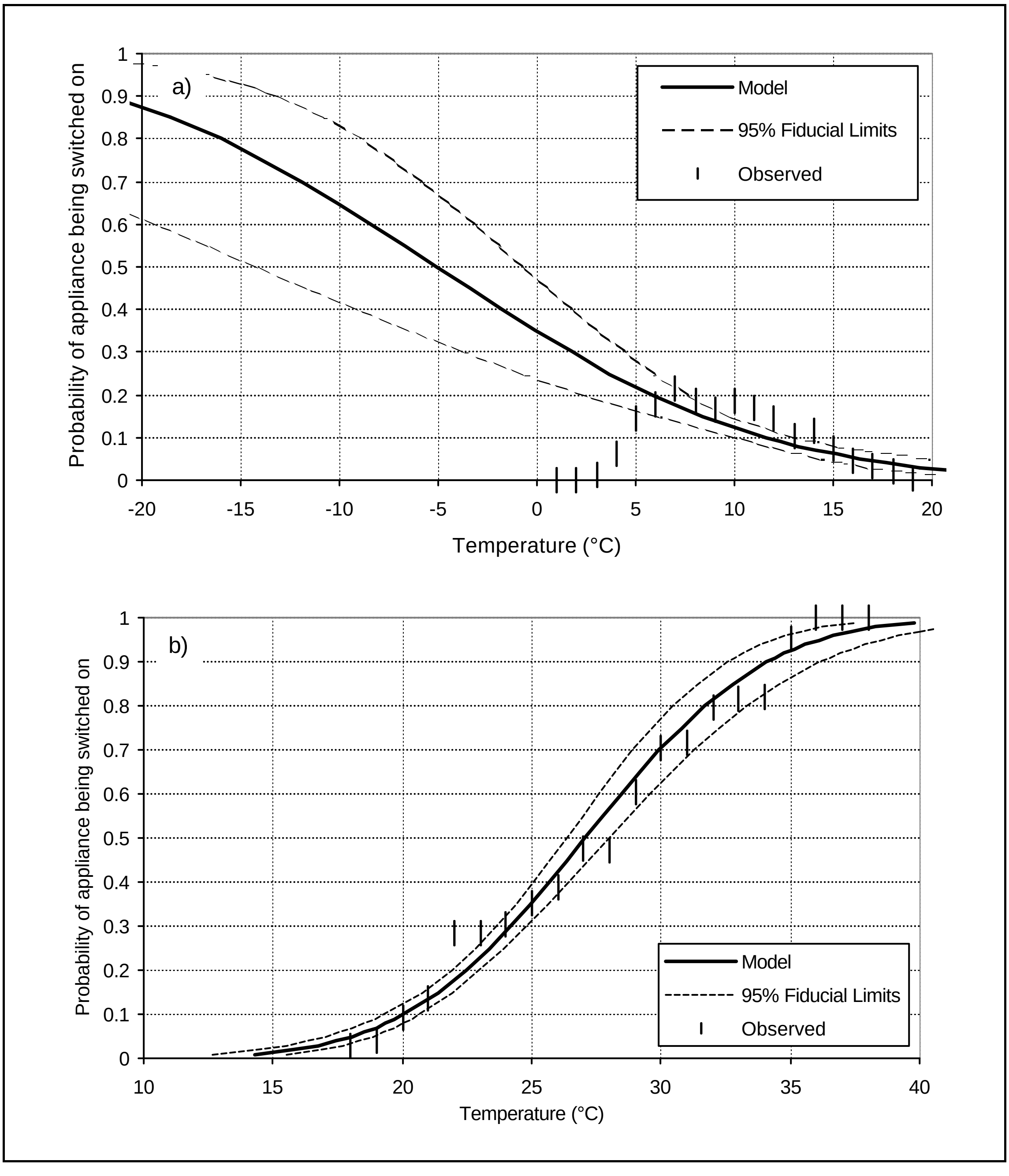


Figure 4.7 Single-household case study. Hourly probit analysis examines the relationship between mean hourly temperature and the fraction of occurrences, for each temperature bin, of the appliance being switched on at "anytime" during each hour of analysis, during a) the heating season and b) the cooling season.

In the heating season (Figure 4.7a) the probability of the appliance being switched on increases with decreasing outdoor temperature, reaching a peak at 6°C but then, contrary to expectations, begins to decrease with further reductions in outdoor air temperature. The chi-square statistic for the goodness of fit test is significant in the heating season ($\div^2=239.3, df=17, P=0$), confirming what is obvious just by looking at Figure 4.7a, namely that the probit model is inappropriate for this set of data. A similar analysis using room heater data produced similar patterns.

4.1.2 Refrigerators/Freezers

Refrigerator and freezer penetration in NSW currently stand at 1.3 and 0.4 appliances per household, respectively (AGO, 1999)

Refrigerator energy consumption has a positive, linear dependence on degree-days, with an increase in energy consumption for an increase in degree-days. There appears to be two distinct sets of data in Figure 4.8a; a cloud of data points appearing just above the fitted regression line and another just below it. There also appears to be a slight change in gradient moving from heating season (-ve degree-days) to cooling season (+ve degree-days).

According to the correlation coefficients in Figure 4.8a above, outdoor temperature bears a closer relationship to refrigerator energy consumption during summer than in winter (R^2= 0.31 and 0.06 respectively). An increase of one degree-day in summer will increase energy consumption by 95Wh/day, whereas the same increase in winter will only increase energy consumption by barely half that amount (42Wh/day on average).

Freezer daily energy consumption also increases linearly with an increase in degree-days. The relationship between energy consumption and degree-days is quite strong with 67% of the day-to-day variance in energy consumption being explained by the degree-day index. This relationship is stronger than that for refrigerators (R^2=0.42). Figure 4.8b depicts the relationship, split by season. As with refrigerators the relationship is stronger in summer (R^2=0.51) than in winter (R^2=0.36). In summer an increase of one degree-day will increase energy consumption by 75Wh/day whereas in winter energy consumption will only increase by 53Wh/day; about 30% less weather sensitive than in summer.

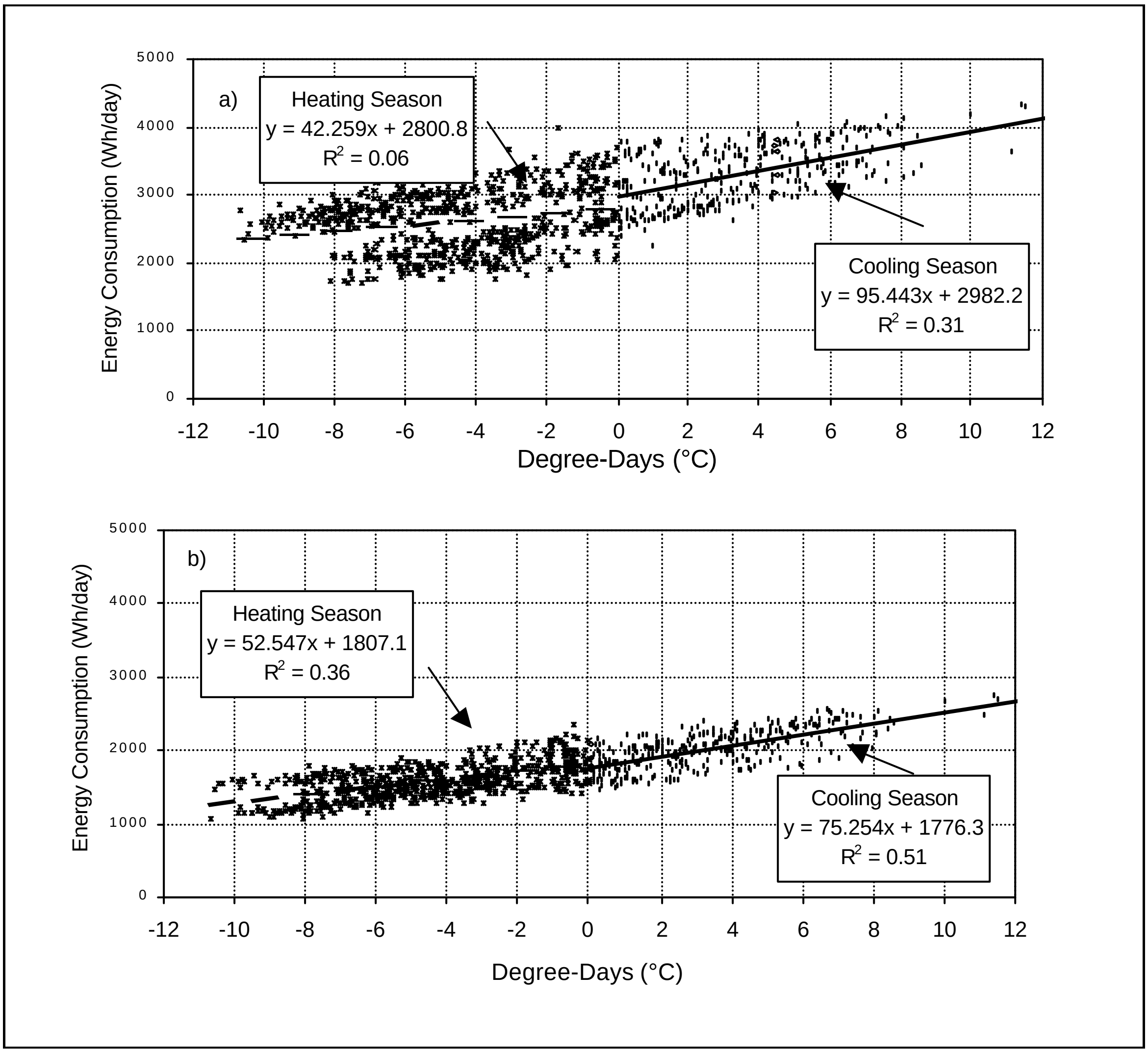


Figure 4.8 The relationship between daily energy consumption and degree-days, split by season (dashed model fitted to the heating season; solid model fitted to the cooling season) for a) refrigerators, and b) freezers. Ninety-three refrigerators and thirty-nine freezers (i.e. households) were included in the analysis.

4.1.2.1 Single-Household Case-Study

The following single house case study explores the relationship between degree-days and refrigerator energy consumption, and includes the effects of space heating and cooling in the household.

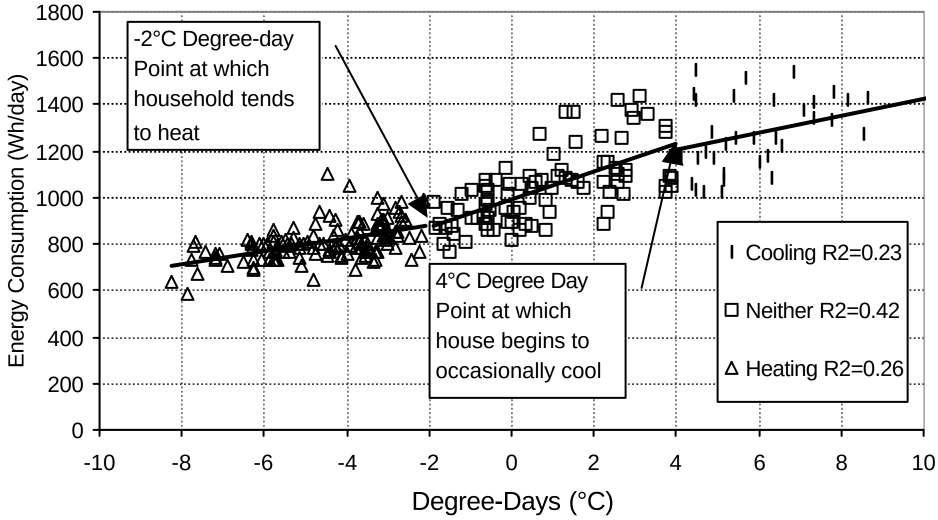


Figure 4.9 A single house case study of refrigerator energy consumption from a household located in coastal Sydney. Refrigerator energy consumption was split into three sections depending on whether the household was being artificially heated, cooled, or free-running.

Energy consumption data for the household's reverse cycle air-conditioner was used to define the outdoor temperatures at which the occupants began to heat or cool their house. Refrigerator energy consumption was split into three sections depending on whether the household was being artificially heated, cooled or free-running. On days below -2°C degree-day the household tended to heat and on days above 4°C degree-days the household tended to cool. On days between the threshold temperatures of -2°C and 4°C degree-days the house was assumed to be free running, neither heated nor cooled. When the household was free-running the relationship between refrigerator energy consumption and outdoor temperature was strongest (R^2=0.42) and the gradient (weather sensitivity) was greatest. As soon as the household was heated or cooled the refrigerator's weather sensitivity was diminished. These points show a change in refrigerator energy consumption, which tends to plateau out once the house is artificially heated or cooled (Figure 4.9).

4.1.3 Domestic Hot Water Systems

Domestic hot water analysis has been split by the different energy rates available to consumers (anytime, off-peak and night-rate). Anytime hot water refers to systems that heat water whenever required, regardless of tariff. Thirty-one anytime hot water units were included in the analysis. Off-Peak systems switch on the water heater between 10pm-8am and 11am-4pm, thirteen of which were included in the analysis. Night-rate hot water is switched on between 12am-7am; forty were included in the analysis.

Seventy-five percent of NSW households currently contain an electric domestic hot water system (AGO; 1999)

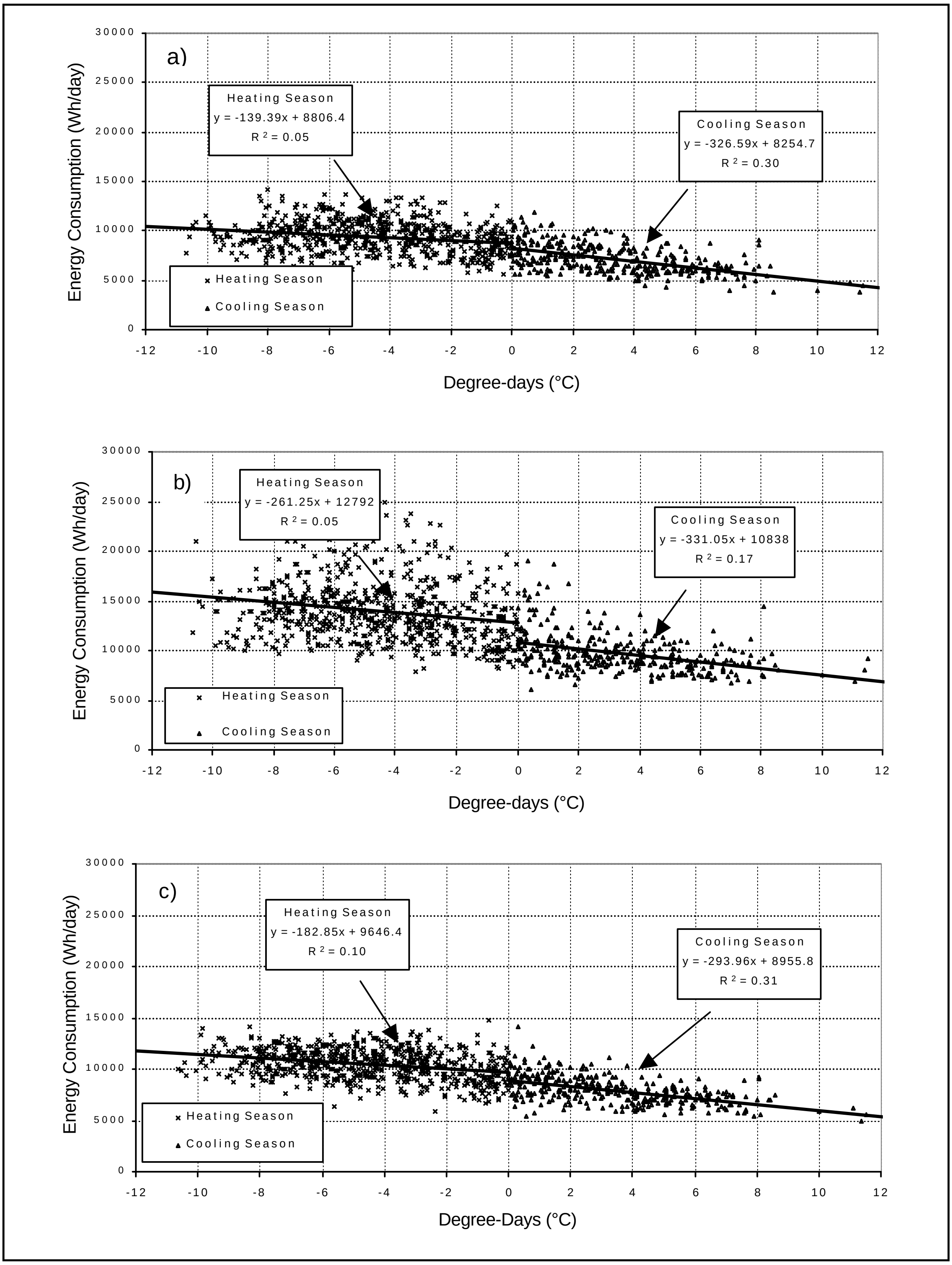


Figure 4.10 The relationship between hot water energy consumption and degree-days, split by season, for a) anytime, b) off-peak, and c) night-rate systems.

For all three types of electric hot water system the relationship with outdoor temperature was negatively linear, with an increase in degree-day value causing a decrease in energy consumption (Figure 4.10). The energy consumption of night-rate hot water systems was affected by outdoor weather most directly (R^2=0.48) (Figure 4.10c), off-peak and anytime hot water systems showing diminished weather sensitivity (R^2=0.37 and 0.38, respectively) (Figure 4.10 a and b). Energy consumption of all three types of domestic hot water systems was affected more by outdoor weather during summer than in winter.

4.1.3.1 Domestic Hot Water Standing Losses

The energy required to maintain the thermostat water temperature in domestic hot water systems without water replacement is termed "standing loss". The value of the standing loss of a hot water system can be determined by interpolating the minimum daily energy consumption from a hot water load profile. This minimum daily energy consumption can be interpreted as the time at which all energy is being used to maintain the thermostat water temperature, i.e. no water replacement is occurring (usually around 4am). As "anytime" hot water is the only mode of hot water where heating is available all day this interpolation was only performed for that type of system (n=31). Standing loss energy was found to increase at a similar rate to that of daily energy consumption, suggesting that the proportion of energy required to recover standing losses was fairly constant throughout the year, at about 36% on average.

4.1.4 Summary of Weather Sensitivity Results

All appliances analysed in this section demonstrated some weather sensitivity. All appliances exhibited stronger weather sensitivity in the summer than in the winter. Space heating and cooling appliances (air-conditioners and room heaters) were found to be the most sensitive to changes in outdoor weather. Space cooling energy consumption demonstrated the strongest relationship with the SET degree-day index, suggesting that relative humidity and wind speed, along with air temperature, all have an effect on house occupants' thermal discomfort and associated thermoregulatory behaviour during the summer. For space heating appliances (air-conditioners in the heating mode and room heaters) simple air temperature degree-days were found to have the strongest relationship with heating energy consumption and usage. The temperature at which space heating and cooling was least required in Sydney was found to be -0.25°C degree-days (corresponding to a mean daily temperature of 17.75°C), remarkably close to the 18°C baseline temperature used for all degree-day calculations in this project.

Freezers were found to be less weather sensitive than refrigerators, however the day-to-day variance in energy consumption attributable to changes in outdoor weather was greater than that for refrigerators (R^2=0.67 for freezers, compared to 0.42 for refrigerators). Off-peak hot water was the most weather sensitive of the hot water systems, however only 37% of the day-to-day variance in energy consumption can be explained by degree-days, compared to 48% by night-rate systems.

4.2 Climatic Impacts Results

Section 4.1 quantitatively defined the climatic sensitivity of various appliances' energy usage on the basis of an 18-month sample (1993-1994); these sensitivities are now applied to long-term climatological observations (1961-1990) and future climatic predictions (2031-2060). These analyses are organised by appliance type.

Monthly degree-day averages were calculated from thirty-year data sets of observed and simulated climate (as outlined in Section 2.3). These monthly degree-day values for the current and future climates were applied to the empirically fitted regression equations of appliance weather sensitivity from the preceding chapter, in order to produce current and predicted energy consumption for different appliances. The scenario for future greenhouse climate was obtained using the delta-T method detailed in Section 2.3.4.

Seasonal differences described in this section are defined as differences in energy consumption between the heating and cooling season. Those months in which the mean degree-day fell below zero constituted the heating season (winter) and months where average degree-day was positive were classified into the cooling season (summer).

4.2.1 HVAC

4.2.1.1 Energy Consumption under a Greenhouse Climate Scenario

Air-conditioning

The statistical relationship observed between air-conditioner energy consumption and outdoor weather (Section 4.1.1) was applied to monthly average degree-days from observed current and simulated future climates. The method simply consisted of inserting a value of degree-days, either current climate or greenhouse scenario, into the relevant appliances' weather sensitivity regression equation from Section 4.1.1. Using this method it was possible to calculate and compare current patterns of air-conditioner energy consumption to those expected under greenhouse climate scenarios.

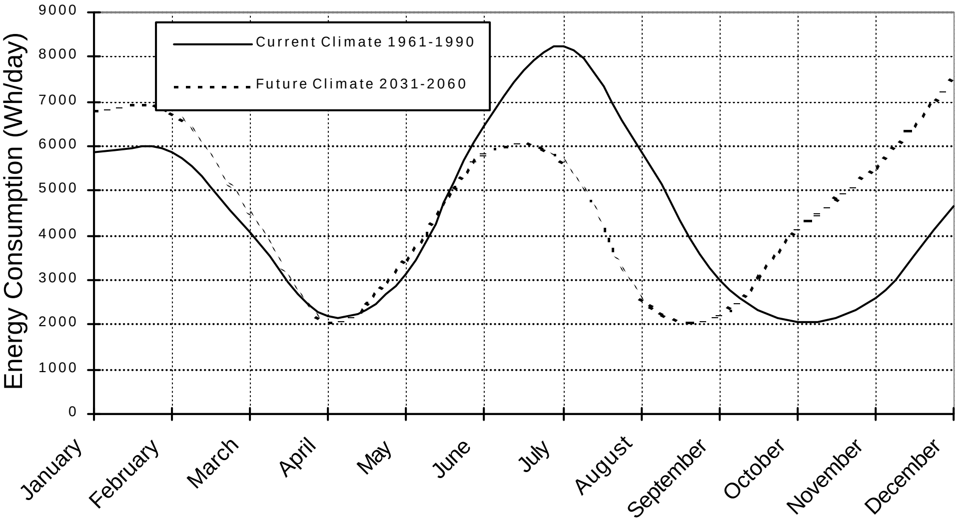


Figure 4.11 Comparison of air-conditioner energy consumption for the current climate and under a future greenhouse climate scenario.

Figure 4.11 details the expected monthly air-conditioner energy consumption under a greenhouse climate scenario, compared to patterns of energy consumption experienced for the current climate. Under a greenhouse climate scenario air-conditioner energy consumption increases by an average 1,320 Wh/day (31%) in summer and decreases by an average 830 Wh/day (19%) in winter, leaving an annual increase in energy consumption of an average 260 Wh/day (6%). Figure 4.11 also shows a shift forward in time for cooling season energy consumption under a greenhouse climate scenario, with the onset of the cooling season predicted to occur in September, compared to October under current climatic conditions.

Room Heaters

The regression equation (observed in Section 4.1.1) linking room heater energy consumption to outdoor weather was applied to monthly average degree-days from observed (current) and simulated (future) climates. This method permits us to project from current patterns of room heater energy consumption to those expected under greenhouse climate scenarios. The results are depicted in Figure 4.12.

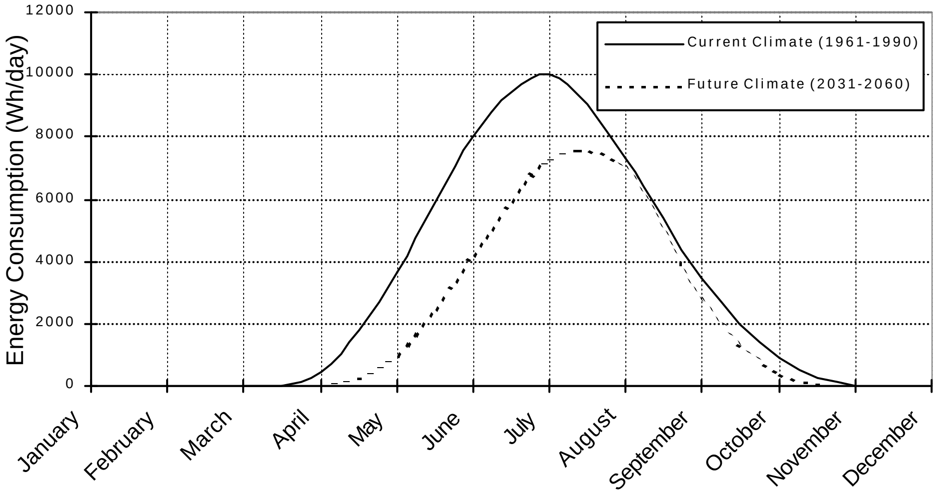


Figure 4.12 Comparison of room heater energy consumption for the current climate and under a future greenhouse climate scenario.

Room heater energy consumption decreased by an average 939 Wh/day under the DARLAM greenhouse climate scenario compared to the observed current climate (Figure 4.12). This amounts to a decrease of 33% in average annual energy consumption by this appliance.

Figure 4.12 also indicates that the onset of the heating season under the greenhouse climate scenario simulated by DARLAM is delayed by at least one month, although the effect is not symmetrical and does not apply to the onset of the cooling season (i.e. heating energy decay).

4.2.1.2 Appliance Usage under a Greenhouse Climate Scenario

Air-conditioning

Probit regression was used in Section 4.1.1.1 to assess the relationship between degree-days and the probability of air-conditioners being switched on. The Probit regression method returns a 50% threshold temperature which represents the temperature (degree-day index) at which 50% of households have their appliance switched off and 50% switched on sometime during the day. The average number of days per month that this 50% threshold was exceeded was calculated for both current and future climates, in order to assess changes in air-conditioner usage patterns under a greenhouse climate scenario.

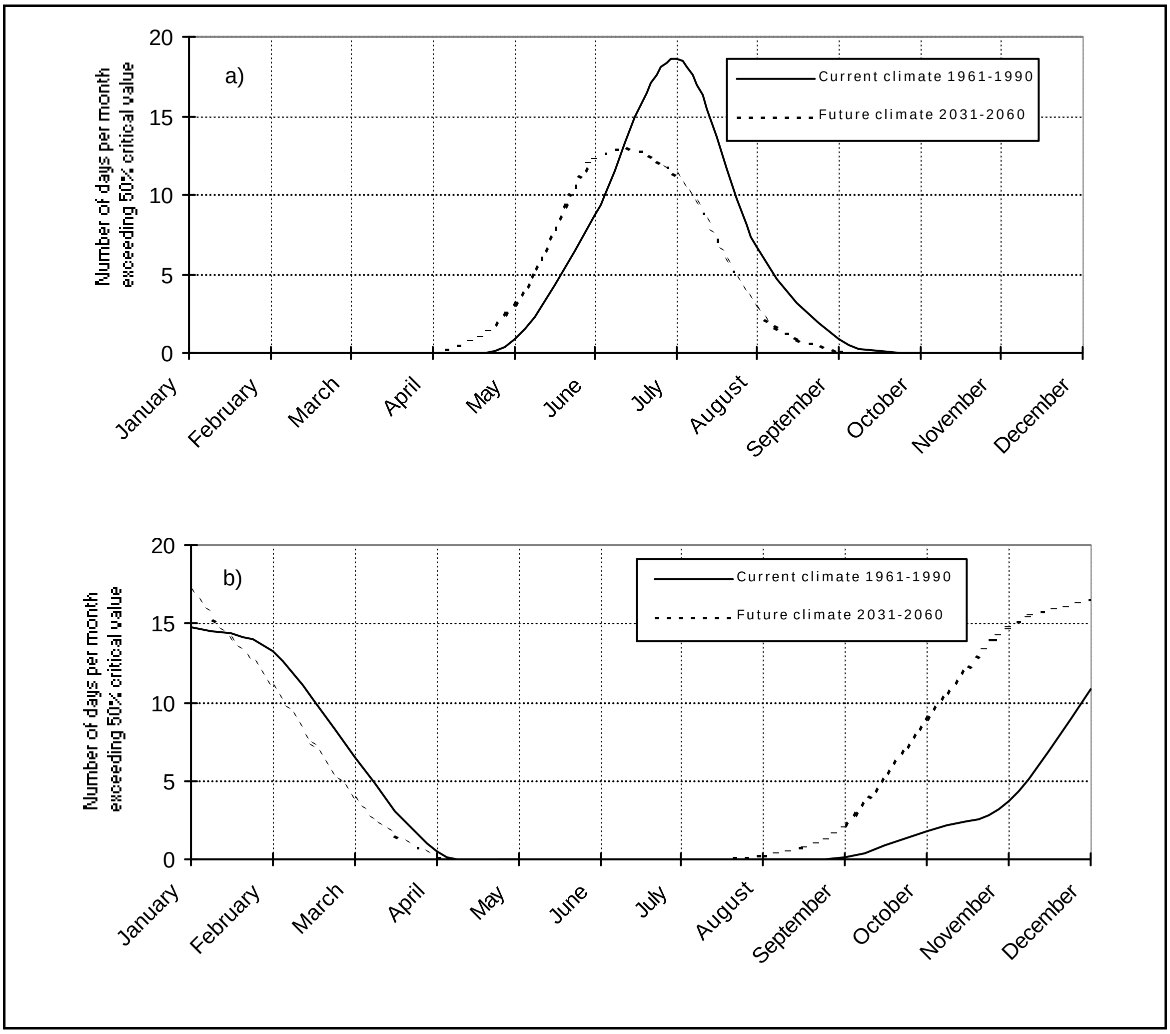


Figure 4.13 Number of days per month, averaged across the thirty year current and future climate datasets, exceeding the 50% threshold temperature in which half of the households have their air-conditioners switched on at sometime during the day, for a) the heating season (50% threshold = 7.1°C degree-days (Figure 4.4a)) and b) the cooling season (50% threshold = 5.5°C degree-days (Figure 4.4b))

During the heating season (Figure 4.13a) there was on average, a decrease of 6.4 days per year, under the greenhouse climate scenario, in which the majority of households would have their air-conditioners switched on to heat; this represents an 18% decrease in the number of majority heating days.

During the cooling season (Figure 4.13b) under the greenhouse scenario simulated by DARLAM there was on average an increase of 23.2 days per year (up 45%) in which the majority of households were predicted to be using their air-conditioners to cool.

Room Heaters

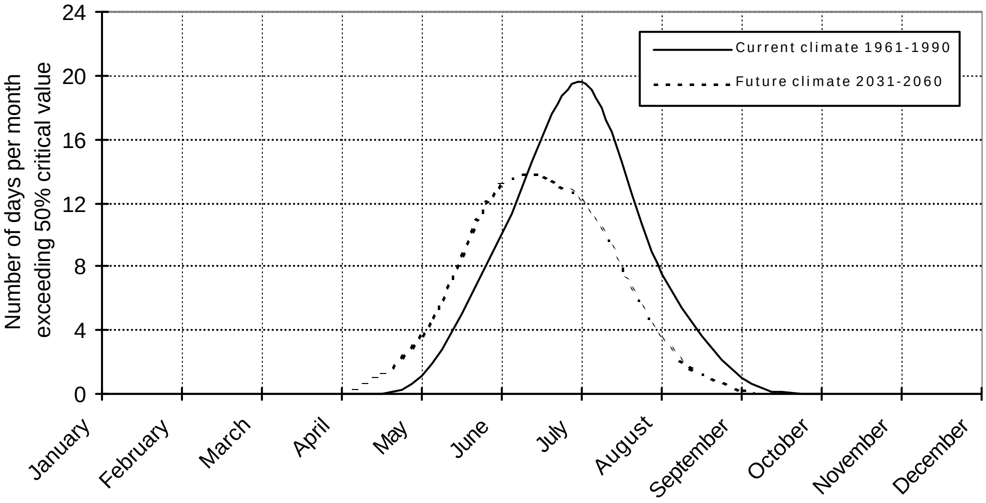


Figure 4.14 The number of days per month, averaged across the thirty year current and future climate datasets, exceeding the 50% temperature (-7.0°C degree-days, Figure 4.5) in which half of the households have their room heater switched on and half switched off.

Using the 50% threshold value calculated from room heater probit analysis (Figure 4.5), the number of days per month exceeding this value for current and future climate was calculated. There was an increase in critical heating days in the greenhouse climate scenario for May and June, but there was a decrease from July through September (Figure 4.14). Over the entire heating season, days exceeding the 50% critical value decrease by 18% under the greenhouse climate scenario simulated by DARLAM.

4.2.2 Refrigerators and Freezers

4.2.2.1 Energy Consumption under a Greenhouse Climate scenario

Using the established statistical relationships (Section 4.1.2) between refrigerator and freezer energy consumption with outdoor weather, energy consumption was calculated for the observed current and simulated future climates. Figure 4.15 illustrates the results.

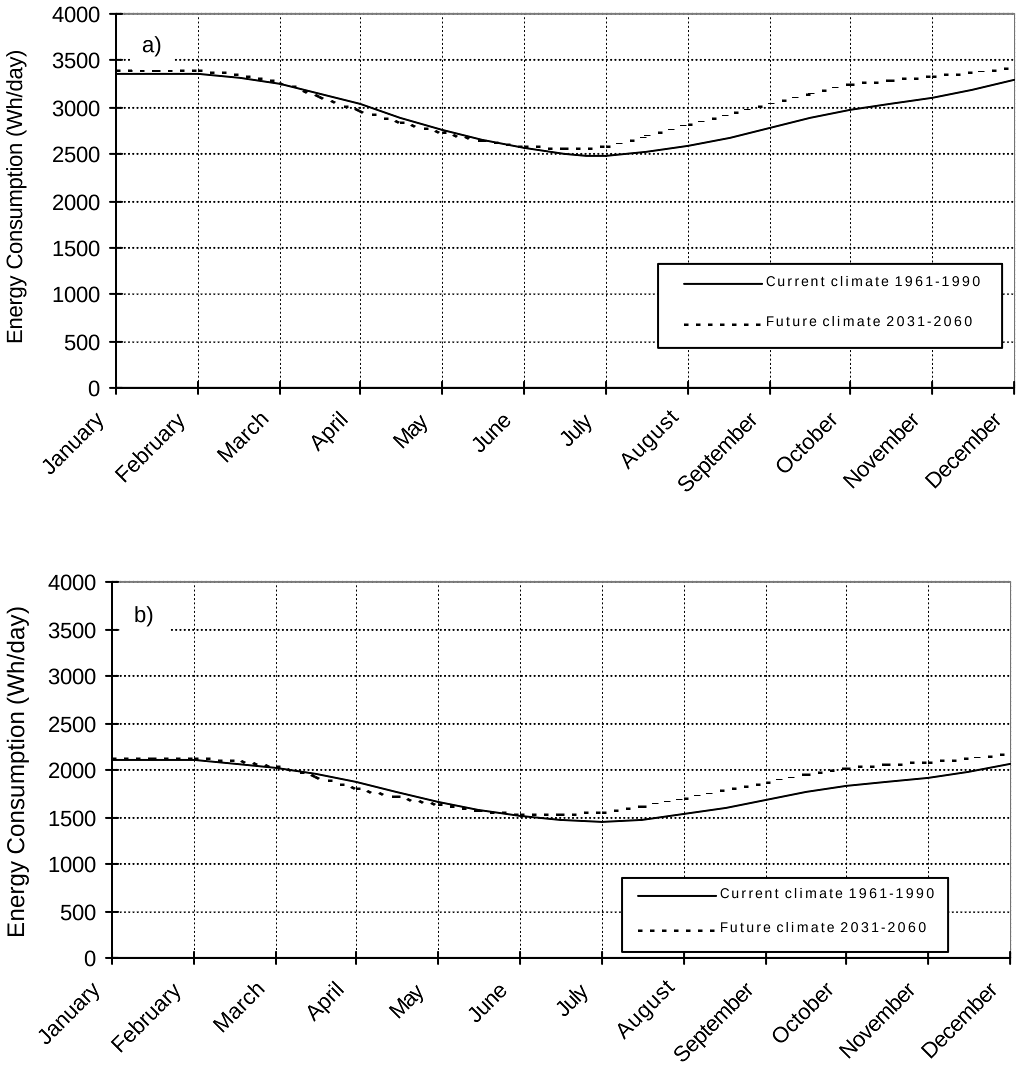


Figure 4.15 A comparison of energy consumption for the current climate and under a future greenhouse climate scenario for a) refrigerators and b) freezers.

Under the greenhouse climate scenario refrigerator energy consumption increased by an average of 109 Wh/day (representing an annual increase of 4%) (Figure 4.15a). Freezer energy consumption increases by an average 82 Wh/day (this is an increase of 5% annually) (Figure 4.15b). Figure 4.15 indicates that energy consumption under the greenhouse climate scenario did not change much in the first half of the year but increased up to 200 Wh/day during the second half of the year.

4.2.3 Domestic Hot Water Systems

Due to the different modes of domestic hot water heating the following analysis of greenhouse climate impacts on energy consumption is split into three sections: anytime, night-rate and off-peak hot water. Anytime hot water is heated at anytime of the day, off-peak hot water is switched on between 10pm-8am and 11am-4pm, and night-rate hot water is switched on between 12am-7am

4.2.3.1 Energy Consumption under a Greenhouse Climate Scenario

The regression equations fitted to the relationships between the three different modes of hot water heating energy consumption and outdoor weather (Section 4.1.3.1) were applied to monthly average degree-days from observed current and simulated future climates. The results are prepared as a set of three graphs in Figure 4.16.

Figure 4.16 details the change in hot water energy consumption under a greenhouse climate scenario. All three modes of hot water heating show a decrease in energy consumption. “anytime” hot water energy consumption decreases by an average 723 Wh/day (this is a decrease of 8% annually) (Figure 4.16a), off-peak consumption decreases by an average 652 Wh/day (an annual decrease of 5%) (Figure 4.16b), and, night-rate hot water energy consumption decreases by an average 397 Wh/day (an annual decrease of 4%) (Figure 4.16c).

For all three modes of hot water heating the decrease in energy consumption is mainly confined to the second half of the year.

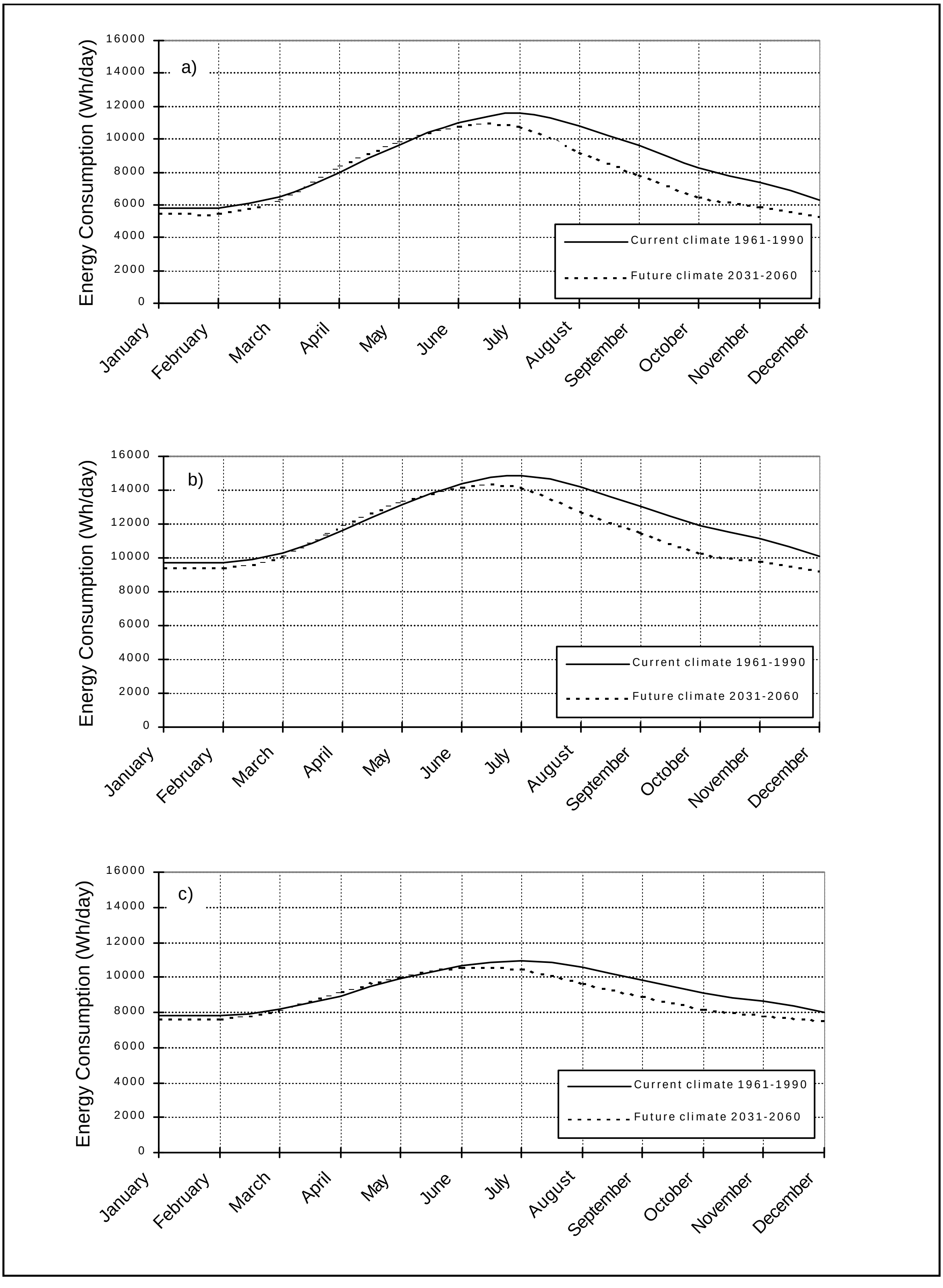


Figure 4.16 A comparison of hot water energy consumption under current and future greenhouse climate scenarios for a) anytime, b) off-peak, and c) night-rate hot water systems.

4.2.4 Summary of Climatic Impact Results

Of the various appliance types analysed in this section space heating and cooling appliances (air-conditioners and room heaters) demonstrated the largest effect of greenhouse climate change. Air-conditioning in cooling mode was impacted most severely. The overall warming of the climate was predicted to reduce heating energy consumption by 19%, however, this was overridden by the associated increase in cooling energy consumption of 31%, leading to an net increase in air-conditioning energy consumption of 6%.

The magnitude and sign of impact of greenhouse climate warming on those appliances containing a temperature regulator (i.e. thermostat) depended on whether the appliance was used for cooling or heating. Due to the overall increase in outdoor air temperature, refrigerator and freezer energy consumption appear to increase by 4% and 5% respectively under the greenhouse climate scenario. Whereas this increase in air temperature can be expected to cause a decrease in domestic hot water energy consumption, this decrease was quite small in terms of net percentage change in energy consumption. However, domestic hot water units are quite energy intensive so the change in terms of absolute energy are relatively significant.

For all appliances analysed in this climatic impacts assessment, the major change in energy consumption is concentrated during the second half of the calendar year, from the end of winter until summer.

5 DISCUSSION

5.1 Weather Sensitivity

5.1.1 An Appropriate Degree-Day Base Temperature for Sydney

The severity of climate can be characterised concisely in terms of degree-days. The degree-day base temperature is generally regarded as the outdoor temperature at which neither artificial heating nor cooling is required. Heating degree-days, or degree-hours, calculated with respect to a base temperature of 18°C are widely accepted in Australia (Badescu and Zamfir, 1999). For cooling degree-days however, the base temperature is not so unanimously agreed. During the heating season the total heat loss coefficient of a building does not change as windows are closed and air exchange rate is fairly constant. However, during the cooling season heat gains can be eliminated and the onset of artificial cooling can be postponed by increasing ventilation rates e.g., opening windows (ASHRAE, 1993). Often different base temperatures are used for cooling degree-days, depending on the building type and ventilation rate. This base temperature is the temperature where artificial cooling begins after a period of increased ventilation. As the building type and level of ventilation were not known for the houses in the present study a cooling degree-day base temperature of 18°C was presumed.

From the results of air-conditioner energy consumption versus degree-days (Figure 4.1), the parabolic minimum occurred at -0.25°C degree-days, so the base temperature of 18°C seems well supported by observations in the Sydney context. The relationships for both seasons demonstrated that, at an average temperature above 18°C in Sydney, householders start their coolers, resulting in the energy consumption rising more rapidly with a rise in cooling degree-days. Similarly for the heating season, with an average daily temperature below 18°C, householders start their heaters, and once again their energy consumption rises more rapidly as the heating degree-day index increases (or becomes more negative in the present study).

It is noteworthy that even at this minimum energy temperature reverse cycle air-conditioners were consuming on average 2kWh/day of energy across the entire sample (Figure 4.1). Similarly probit analysis of reverse cycle air-conditioners (Figure 4.4) showed that on a zero degree-day (°C) (using an 18°C base temperature) 20% of households used their air-conditioner for heating or cooling purposes at some time during the day. This is showing that there are significant differences in base temperatures from one household to the next. The case study of an individual reverse cycle air-conditioner (Section 4.1.1.3) demonstrated how a particular Sydney household began heating on a -3.5°C heating degree-day and cooling on a +2°C cooling degree-day. Therefore 14.5°C and 20°C heating and cooling degree-day base temperatures respectively might have been more appropriate just for that particular household. However, averaging across all 47 households in the present study, it appears as if the year-round 18°C base temperature was most appropriate.

5.1.2 HVAC

As one might expect, this study has demonstrated that air-conditioner energy consumption is reliant to a large extent on outdoor weather. The variation of energy consumption between individual machines obviously depends on their capacity (heating and/or cooling), efficiency (age), household socio-economic variables such as income, occupant behaviour, whether or not the occupants are home, and of course inter-individual differences in thermal discomfort thresholds. Despite all of these potential influences, diurnal, synoptic and seasonal variability in the outdoor atmospheric environment (air temperature, relative humidity and wind speed, as integrated within the SET degree-days index) accounted for nearly half (45%) of the variance in daily air-conditioning energy consumption during this 18-month study of 47 Sydney households.

According to NatHERS (National Housing Energy Rating System) (CSIRO, 2001), other factors affecting an individual household's space heating and cooling energy consumption include; house construction type, age, nature of the building shell materials, window style and size, house floor plan area, number of rooms, solar gains, shading, and the level of insulation in ceilings, walls and floors. These factors, together with house to house variations in occupancy would probably account for much of the variance left unexplained by outdoor weather indices.

From our probit regression results (Section 4.1.1.1), degree-days expressed in terms of simple air temperature appeared to be the most useful predictor of the likelihood that air-conditioners were switched on during the heating season (Figure 4.4a). The atmospheric parameters of humidity and wind which are included in the comfort indices of ET* and SET respectively, appear not to add significantly to the explanatory power of plain air temperature during the winter air-conditioner analysis. However, during summer, wind speed and humidity in addition to ambient temperature have significant effects on our thermal comfort, therefore the SET degree-day index turned out to be the most significant predictor of when householders switched air-conditioners on for cooling.

Probit analysis of the likelihood that air-conditioners were switched on at anytime during the day in relation to degree-days (Figure 4.4) revealed that, during the heating season on the coldest of Sydney days, only 65% of households were switching on their air-conditioners. However, during the cooling season, on the warmest of Sydney days, about 90% of households switched on their air-conditioners. Those houses not using their air-conditioners during these extreme days may not be occupied (for example, at work). Unfortunately occupancy could not readily be diagnosed from the raw data collected in the RES. The database contained appliance energy audit data but nothing on occupant behaviour or demographics. The relatively large proportion of households choosing not to use their air-conditioners to heat on Sydney's coldest days may indicate that they were using alternative forms of heating (i.e. not reverse cycle air-conditioning). Many Sydney households have several space heating devices of various energy types and use them interchangeably and/or simultaneously, making it difficult to measure heating demand (AGO, 1999). For example, 55% of households monitored in the Residential Energy Study had at least one gas appliance, which could quite possibly include a gas heater.

Room heater probit analysis produced similar results to the heating mode of air-conditioners, in that the coldest of Sydney days saw only 63% of households switch their heaters on. Of the 27% of households not switching on their electric heaters, some may be using alternative forms of heating such as reverse cycle air-conditioners, gas heaters, wood-fired heaters etc. Occupancy patterns and individual differences in thermal discomfort thresholds will also have an effect on the proportion of appliances switched on at any time. A similar Household Energy End-use Project (HEEP) in New Zealand (Isaacs, 1997) indicated that, across a range of household appliance types similar to those monitored in the present Residential Energy Study, heating had the largest variation in weekly energy consumption. The study compared heating daily energy consumption with indoor and outdoor average daily temperatures for one household over four months, but failed to find a strong relationship with either parameter. The Isaacs (1997) study merely confirms the need for a reasonable sample size, because the presents study's sample of 71 households revealed a significant impact of outdoor weather variations on room heater energy end-use.

The relationship between outdoor weather and air-conditioner energy consumption is much stronger in summer than in winter (R^2=0.56 for summer, compared to 0.35 for winter). Air-conditioner load profiles (Figure 4.6) indicate that peak energy consumption occurs in the late afternoon during summer and in the evening during winter. Temperature minima occur in the early morning and maxima in the mid afternoon. Consequently during the heating season at the coldest time of the day, occupants are sleeping and, as a result, energy consumption is minimal. The lack of heating during this coldest time of the day undoubtedly weakened the statistical relationship between daily energy consumption and heating degree-days, suggesting that time-of-day is a critical factor in the prediction of space heating energy consumption. This point was confirmed by the single appliance case study detailed in Section 4.1.1.3. Probit analysis of the proportion of time the appliance was switched on (Figure 4.7) indicated a maximum usage at 7°C. But the proportion of hours the appliance was switched on decreased sharply as temperature decreased below 7°C, presumably because the householders were asleep. By way of contrast, during the cooling season (summer) when air-conditioner load peaks in the afternoon (coinciding with the warmest time of the day), house occupants are more likely to be awake, thus explaining the stronger statistical relationship between daily energy consumption and cooling degree-days.

5.1.2.1 Space Heating and Cooling Load Prediction

In most electricity systems the residential sector is one of the main contributors to system peak loads (Bartels and Fiebig, 1996). For space heating and cooling the appliance end-use contribution to the system peak appears to be driven mainly by weather. Energy companies may be able to use the probit models produced in Sections 4.1.1.1, in conjunction with weather forecasts, to predict days when outdoor weather will cause a system peak.

One of the key outputs from the probit regression tool is a 50% threshold temperature; the temperature at which the largest proportion of households change their appliance from “off” to “on”, this could cause a system spike in electricity consumption. These results, along with the load profiles produced in Section 4.1.1.2, and the direct relationships produced between energy consumption and outdoor weather (Section 4.1.1) may potentially be useful for power utility operations in predicting system spikes and peaks in the Sydney market. The end-use load profiles for each appliance give the time of day when a system peak can be expected. From space heating and cooling load profiles (Section 4.1.1.2), system peaks occur at 4pm during the cooling season and 8am and 9pm for the heating season. Probit curves used in this report give the type of day when a system peak can be expected. At the time of writing a service, called eWeather Online (2001) provides eight-day weather (from CSIRO's Division of Atmospheric Research) and electricity demand forecasts (from the National Electricity Market Management Company's (NEMMCO), Short Term Projected Assessment of System Adequacy (STPASA)) for wholesale electricity sellers and buyers. The information is used to forecast possible spikes in electricity demand, across all sectors (Trewin, 2001). This report has produced a comprehensive description of the weather sensitivity of electricity end-use in the residential sector. Since the residential sector in general and space heating and cooling appliances in particular have a large impact on electricity peak loads (Bartels and Fiebig, 1996), the weather sensitivity results from this report, along with appliance penetration rates, are potentially useful in looking at systems peaks in relation to individual end-uses.

5.1.3 Refrigerators/Freezers

Outdoor temperature has a stronger influence on refrigerator energy consumption in summer than winter (R^2=0.31 for summer, compared to only 0.06 for winter). Furthermore, an increase of one degree-day in summer produces an increase in refrigerator energy consumption more than double that for a comparable temperature increase in winter.

One possible explanation of this enhanced weather sensitivity in summer may be the fact that the householders were heating the rooms in which the refrigerators were located during winter months. Modifying the interior temperature through space heating breaks the nexus between outdoor temperature and refrigerator energy consumption, as shown in the single household case study detailed in Section 4.1.2.1. At the time of the Residential Energy Study (1993/1994) Sydney's peak in electricity consumption typically occurred in winter (Camilleri *et al.*, 2000), suggesting that households were choosing to artificially heat more readily than cool. A similar residential end-use study in France (Sidler, 1997) also noted that refrigerator energy consumption was strongly correlated to temperature in summer, but was less weather sensitive in winter due to household heating. Refrigerator energy consumption in the French summer was 29% greater than in winter, which compares quite closely to Sydney's results in this project (27%).

Current refrigerator test procedures for use in Minimum Energy Performance Standards (MEPS) and energy efficiency labelling schemes take place using one reference ambient temperature inside a controlled laboratory. This ambient temperature differs world wide, from 30°C in Korea, Japan and Chinese Taipei to 32°C in USA, Australia and New Zealand. The International Organization for Standardisation (ISO) specifies 25°C for temperate climates and 32°C for tropical climates (Harrington, 2001). In reality refrigerators operate under a range of ambient temperatures, and energy consumption and performance will vary under these non-steady-state conditions, as demonstrated by the results of this study. The aim of energy labelling is to encourage customers to purchase the appliance that uses the least energy during *actual* use. A test procedure undertaken at a single temperature will not demonstrate the appliance's performance under realistic ambient conditions. For example, the French Domestic Measurement End-use Campaign (Sidler, 1997) discovered that *in situ* energy consumption in refrigerators is lower than the energy consumption measured under laboratory test conditions. The linear relationship between an average of ninety-three refrigerators' daily energy consumption and degree-days in this study could potentially help in the design of a more realistic and representative refrigerator test protocol.

Freezer daily energy consumption increases linearly with an increase in degree-days (see Figure 4.8b). The relationship between energy consumption and degree-days is quite strong with two thirds of the day-to-day variation in energy consumption being explained by concurrent degree-days. This relationship between freezer energy consumption and degree-days is stronger than that for refrigerators (R^2=0.42 for refrigerators, 0.67 for freezers), possibly due to freezers not being accessed as often as refrigerators, and as a result, fewer door openings (heat gains) and changes to food load. Freezers are also likely to be located in a part of the house that is not subject to temperature control (heating or cooling). There was an increase of 30% in freezer energy consumption per degree-day from winter to summer, compared to an increase of 50% in the French end-use study (Sidler, 1997). The French study also found that similar to refrigerators, freezers tend to consume less energy in practice than under controlled laboratory test conditions.

5.1.4 Domestic Hot Water

Domestic hot water energy consumption shows a stronger relationship to outdoor temperature in summer than in winter (for anytime hot water systems, R^2=0.30 in summer and 0.05 in winter). Furthermore, the weather sensitivity of summer hot water

$_1$=-327 (Wh/day)/degree-day compared to –139 (Wh/day)/degree-day). Depending on the mode of the hot water system between 30 and 48% of the day-to-day variation in energy consumption can be explained by changes in outdoor weather. In the case of outdoor hot-water storage systems, an increase in outdoor temperature will decrease the amount of heat lost to the environment from the hot water cylinder, therefore requiring less energy to heat the hot water to thermostat temperature. A large amount of the unexplained variance in hot water energy consumption could be due to many hot water systems being located indoors rather than outdoors, but unfortunately this hypothesis could not be investigated any further because the physical location of the hot water appliance was not available in the RES database. Other factors, apart from weather, affecting hot water energy consumption include the nature of other hot water consuming devices such as dishwashers and washing machines, the nature (insulation status) of the distribution pipes, and occupant behaviour. The weather sensitivity of hot water energy consumption may further be increased in summer due to occupants' thermal comfort preferences. For example an increase in outdoor temperature may prompt occupants to prefer cooler showers that require less hot water.

The temperature of the main water supply, which varies seasonally, also influences energy consumption of a hot water service. As water supply temperature drops, more energy is required to heat it up to the thermostat temperature (typically up to 75°C degrees in Sydney (Harrington, 2001b)). The New Zealand Household Energy End-Use Project (Isaacs, 1997) discovered that 44% of domestic hot water energy consumption was used to recover standing losses. In the present study 36% of the total energy consumed by anytime hot water systems was required to recover standing losses. Sydney's mild climate compared to New Zealand may explain this difference. Warmer ambient and water supply temperatures result in less energy required to maintain the temperature of the water in the system.

5.2 Climate Change

The Inter-Governmental Panel on Climate Change (IPCC) reports that the impacts of climate change on residential energy consumption will be perceptible but modest in relation to the impact factors such as changes in technology and patterns of economic activity (Scott *et al.*, 2001). Adaptability is high in the residential energy sector. However, for changes in technology and policy to occur it is necessary to appreciate the impact of "business as usual" on residential energy consumption under a greenhouse climate. In short, “business as usual” predictions can act as an impetus for technological and operational adaptation and mitigation; consumer change will not occur unless the costs of not changing are made abundantly clear. The present report projects current usage patterns and appliance efficiencies (business as usual) onto future climate scenarios, *ceteris paribus*.

Since all appliances included in the present analysis showed some degree of weather sensitivity they would all be impacted to varying extents by climate change. The appliances included in the current analysis constitute 53% of current household greenhouse gas emissions (AGO, 2001). Depending on the nature of the appliance, energy consumption either increases or decreases under a greenhouse climate. Those appliances containing a cooling mode (air-conditioning, refrigeration and freezers) demonstrated an increase in energy consumption, whereas appliances involved in heating (air-conditioners in heating mode, room heaters and domestic hot water) decreased their energy consumption. The major change in energy consumption for all appliances occurred in the second half of the calendar year, particularly during spring months, coinciding with the most intense change in climate under a greenhouse climate scenario, as simulated by DARLAM.

Since the main weather sensitive appliances were included in the present analyses it seems reasonable to speculate about the net effect on household energy consumption under a greenhouse climate scenario. For a household located in Sydney, with a reverse cycle air-conditioner, a refrigerator, freezer and a domestic hot water system on night-rate tariffs, the net change in energy consumption under a greenhouse climate scenario would be an increase of 2%. However, for a household containing a room heater, a refrigerator, “anytime” hot water and no form of space cooling device the net change in energy would be a reduction of 10%.

Rosenthal *et al.* (1995) estimated the impact of global warming on US energy expenditures for space heating and cooling in residential and commercial buildings. Average results from six GCMs were used to estimate the change in heating and cooling degree-days in five US climate zones in response to a modest 1°C global warming in 2010. Results indicated an increase of cooling season energy consumption of 20%, a decrease of heating season energy consumption of 6% and an overall decrease in annual energy consumption of 11%. The study also took into account regional differences in population and baseline space conditioning intensity levels across regions.

Rosenthal *et al.* (1995) assumed that space conditioning energy requirements are approximately proportional to degree-days. This method of predicting space conditioning energy requirements can be compared to methods used in the current study. Space conditioning energy consumption for Sydney, under a greenhouse climate scenario was calculated using both methods and they both produced the same results for the heating season, with a decrease in heating season energy of 19%. However, applying the Rosenthal *et al.* proportionality assumption, the change in cooling season energy consumption was greatly underestimated; our sensitivity equations estimated an increase in air-conditioner cooling season energy consumption of 31% compared to only 2% based on Rosenthal *et al.*'s proportionality assumption.

5.3 Limitations to the Present Study

Only electrical appliances were monitored in the Residential Energy Study (Camilleri *et.al*., 2000) that formed the basis of the current report. The inclusion of gas appliances would have given a more comprehensive picture of residential energy consumption in Sydney. Fifty-five percent of the households monitored had at least one gas appliance, however data on which households they were and the nature of those appliances was unavailable. This would have been particularly useful in the analysis of space heating where a large proportion of Sydney households are known to use gas appliances; a point suspected to explain why, on the coldest of Sydney days, only 65% of households switched on their electric heating appliances.

Greenhouse climatic impact assessments were undertaken only on changes in air temperature degree-days. They did not take into account any of the other weather parameters known to be important to human comfort and demonstrated to influence air-conditioner usage and energy consumption in this project, i.e. humidity and wind speed which were shown in Section 4.1 to significantly improve weather sensitivity models (enlarged R^2), especially during the cooling season.

It was noted that there were complex interactions between appliances - for example, the use of indoor heating attenuated the weather sensitivity of domestic refrigeration and freezing energy consumption. Therefore it would have been interesting to analyse how greenhouse climate change impacted the *total* electricity load of households. Although total load was monitored for each household in the RES database these data were not used in the analysis because the total load typically excluded appliances that were separately wired to the household's fuse-box. For example, refrigerators and freezers are often wired on separate circuits to minimise food spoilage after fuse-blows and they would therefore be omitted from the household's total metered consumption.

6 CONCLUSIONS

6.1 Summary

The objective of this report to examine weather and climate sensitivities of household appliance energy end-use. Appliance energy data from a Residential Energy Study were analysed in conjunction with concurrent weather data. The resulting statistical relationships were then applied to long-term climatalogical observations (1961-1990) and future greenhouse climate scenario predictions (2031-2060), in order to project potential impacts of climate change on household appliance energy end-use.

The first aim of the report was to:
Quantify the dependence of residential appliance energy consumption on the outdoor atmospheric environment in Sydney.

Statistical models were established between outdoor weather and energy consumption for each appliance in Section 4.1. All appliances exhibited some form of weather sensitivity. These relationships provide actual in-use energy consumption rather than laboratory consumption, and this in turn may be used to design more realistic and representative appliance test protocols (often used in the implementation of MEPS). Probit models of space heating and cooling appliance usage patterns can predict the probability of the appliances being switched on under various outdoor weather conditions. These relationships, along with load profiles and the direct relationships produced between energy consumption and outdoor weather, have the potential to assist in the prediction of system spikes and peaks.

The second objective of the report was to:
Define the most appropriate thermal climate index affecting energy consumption for space heating and cooling.

Standard Effective Temperature (SET) degree-days, integrating the effects of air temperature, wind speed and relative humidity, were found to produce the strongest relationship with appliance usage during summer. During winter relative humidity and wind speed did not add significantly to explanatory power of plain air temperature. Therefore the most appropriate index of climate was clearly SET degree-days during the cooling season, but regular air temperature degree-day calculations are satisfactory in the heating season.

The third objective of the report was to:
Analyse appliance usage thresholds and assess whether they hold true to current heating and cooling degree-day base temperatures.

Degree-days are universally used in the Heating, Ventilating and Air-conditioning industry to relate outdoor weather to appliance energy consumption. By examining the mean daily temperature associated with minimum heating and cooling energy consumption for Sydney, a degree-day base temperature of 18°C was found to be the appropriate base temperature for the calculation of both heating and cooling degree-days. This report is the first analysis to date which empirically confirms that 18°C is the most appropriate degree-day base temperature for Sydney, all-year-round.

The final objective of the report was to:
Project future appliance energy end-use by applying empirically derived weather sensitivity factors to greenhouse climate scenarios for the Sydney region.

The statistical relationships between outdoor weather and appliance energy consumption empirically established under current atmospheric conditions were used to project future energy demand under greenhouse climate scenarios. Future climate was obtained from greenhouse climate simulations from the DARLAM climate model, which were superimposed on long-term observed current climate observations from Sydney using the Delta-T method. The consequences of a net increase in mean temperature for Sydney included an increase in energy consumption for cooling devices, such as air-conditioners, refrigerators and freezers, and a decrease in energy consumption for heating devices; reverse-cycle air-conditioners in heating mode, room heaters and domestic hot water. This was the first climatic impacts assessment undertaken on household appliance energy usage in Australia, and the implications of this “business as usual” assessment should provide additional impetus for technological and policy adaptation and mitigation strategies.

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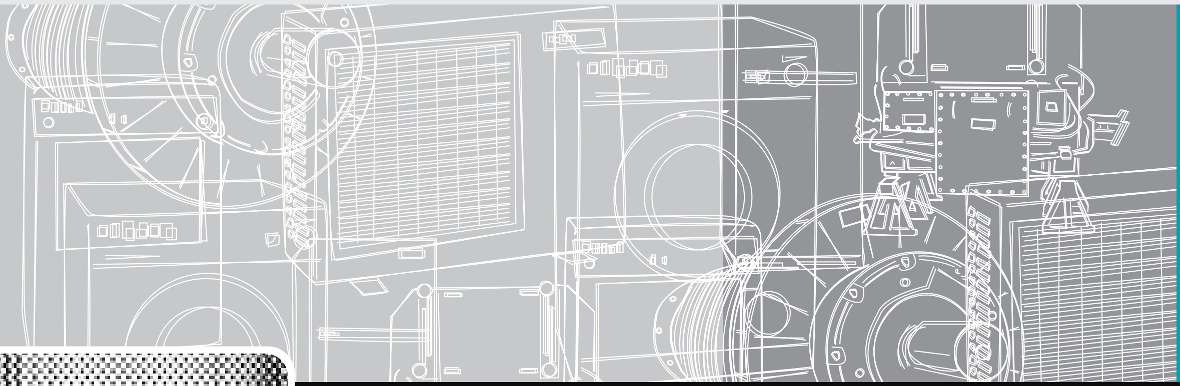

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