Available online at www.sciencedirect.com
ScienceDirect
Atmospheric Environment 40 (2006) 5543–5557
ATMOSPHERIC ENVIRONMENT
www.elsevier.com/locate/atmosenv

Modelling PM_{10} concentrations and carrying capacity associated with woodheater emissions in Launceston, Tasmania

Ashok K. Luhar*, Ian E. Galbally, Melita Keywood

CSIRO Marine and Atmospheric Research, PMB 1, Aspendale, Vic. 3195, Australia

Received 6 February 2006; received in revised form 9 May 2006; accepted 10 May 2006

Abstract

Launceston is one of the Australian cities most affected by particle pollution due to the use of woodheaters in the winter months, with frequent exceedences of the national standard, the National Environment Protection Measure for Ambient Air Quality (or Air NEPM in short), of 50 micrograms per cubic metre for daily PM_{10} (particulate matter with an aerodynamic diameter of 10 μm or less). The main objective of the present study was to determine the woodheater carrying capacity for Launceston—the number of woodheaters that can operate in the city without exceeding the Air NEPM. For this purpose, a prognostic meteorological and air pollution model called TAPM is used, coupled to a gridded woodheater PM_{10} emissions inventory. The latter was derived using information on dwelling density, the percentage of dwellings with woodheaters, woodheater emission rates and their diurnal and seasonal variations, and the proportions of compliant/non-compliant woodheaters and open fireplaces. The model simulations are performed for the year 1998, and the concentrations are scaled for previous and subsequent years using trends in woodheater numbers and types. The modelled number of exceedences of the Air NEPM for the period 1997–2004 is in good agreement with the observations. The modelling indicates that the PM_{10} Air NEPM would be met in Launceston when the total number of woodheaters is 20% of the total number of dwellings, of which 76%, 18%, 6% would be compliant woodheaters, non-compliant woodheaters and open fireplaces, respectively. With the present trends in the regional woodheater profile, this should occur in the year 2007.

Keywords: TAPM; Woodsmoke; Woodheaters; Emission inventory; Air pollution modelling; Particulate matter; Carrying capacity

1. Introduction

The Australian city of Launceston, with a population about 72,000 is located in northern Tasmania's Tamar Valley (147°10′E, 41°27′S), approximately 50 km inland from Bass Strait, on the headwaters of the Tamar River (Fig. 1) and 160 km north of the city of Hobart. The valley axis is mostly aligned in a northwest to southeast orientation and is flanked by hills that reach heights of up to 400 m. Launceston is one of the Australian cities most affected by woodsmoke particle pollution. The woodsmoke problem in Launceston primarily occurs during colder months due to a high level of domestic woodheater use. In the year 2000, around 45% of Launceston households relied

*Corresponding author. Tel.: +61 3 92394400; fax: +61 3 92394444.
E-mail address: ashok.luhar@csiro.au (A.K. Luhar).

1352-2310/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.atmosenv.2006.05.036

Fig. 1. Map of northern Tasmania showing Launceston, the Tamar Valley and Tamar River. The valley axis is mostly aligned in a northwest to southeast orientation and is bounded by hills that reach heights of up to 400 m.

on woodheaters as their main source of heating, with woodheaters accounting for 85% of the PM_{10} observed in the city (Environment Australia (EA), 2001). The topography of the Tamar Valley aggravates the pollution build-up under nighttime temperature inversions in the winter (Kesby et al., 2002).

There is in Australia a National Environment Protection Measure for Ambient Air Quality (or Air NEPM in short) standard (see http://www.ephc.gov.au/nepms/air/air_nepm.html) for PM_{10}. According to the Air NEPM, a PM_{10} exceedence occurs when the 24-h averaged PM_{10} concentration is greater than 50 $\mu g\,m^{-3}$. The goal of Air NEPM with regard to PM_{10} is to have no more than five exceedences per year by 2008. Particulate matter of this size is small enough to be inhaled into the deepest parts of the lungs, with associated adverse health impacts, including increased mortality rates and hospital admissions for respiratory and cardiovascular disease (e.g., National Environment Protection Council (NEPC), 1998).

Launceston in 1997 and 1998 had 40–50 PM_{10} exceedences per year evidently caused by woodsmoke. A key issue for local authorities has been how to manage this woodsmoke problem. There have been public education programs and the number of woodheaters in Launceston has steadily decreased, approximately halved over the past 10 years. The Launceston Woodheater Replacement Programme (LWHRP) was implemented by the Department of the Environment and Heritage (DEH) of the Australian Government in mid-2001. This programme offers rebates to householders to replace woodheaters with heaters that contribute to improved air quality. The principal objective of the work presented here is to determine through a combination of historical measurements, airshed modelling and inventory calculations, the carrying capacity for woodheaters of the Launceston airshed so that the Air NEPM for PM_{10} is not exceeded. The carrying capacity is defined here as the number and type of woodheaters that can operate within the Launceston airshed, while the NEPM goal is met. This information is used in the LWHRP and other pollution reduction strategies to provide target woodheater numbers, and to assess future scenarios involving different proportions of woodheater types.

2. Observed PM_{10} concentrations in Launceston

In Launceston, PM_{10} has been measured at the Ti Tree Bend ambient air quality monitoring station, located approximately 2.5 km northwest of the Launceston city centre, using high volume sampling with varied frequency. Some details of the sampling are necessary to understand the subsequent analysis. In 1992 and 1993, the months of May–August were sampled every second day, while the other months were measured on a one-day-in-six cycle. Between October 1993 and April 1994, no sampling was carried out. From April 1994 to 1996 a one-day-in-six sampling programme was carried out. From 1997 to 2000 a one-day-in-six sampling programme for the summer months of October–April, and a daily sampling programme for the other months was undertaken. Daily sampling started from May 2001. During November 2002–March 2003, although there were daily measurements, there was some data loss due to the cleaning of sludge pits near the station.

The record of PM_{10} exceedences at Ti Tree Bend, presented in Fig. 2, shows a decrease in exceedences between 1992 and 1996 followed by a sudden increase in exceedences in 1997 and a subsequent decrease through to 2002, with a slight increase in 2003. These trends reflect changes in both the frequency of sampling, the season of sampling, and the frequency of occurrence of exceedences. Thus, the low number of exceedences observed in 1994, 1995 and 1996 may reflect the low number of PM_{10} measurements made in those years.

When analysing the data from the more intensive sampling years (i.e. 1997–2003) on a monthly basis, the warmer months of September–March experienced one or no exceedence. During the cooler months of May–August, subsequently described as winter, the greatest number of exceedences was observed in July (80), followed by June (61), May (46), August (32) and April (6). The values of the single highest 24-h averaged PM_{10} concentration observed for the years 1997–2003 were 123, 124, 93, 110, 81, 76 and 75 $\mu g\,m^{-3}$, respectively. The maximum concentration of 124 $\mu g\,m^{-3}$, observed in the year 1998, was measured in July. The infrequent exceedences during October–March, subsequently described as summer, when woodheater use is at the minimum in Launceston, are generally associated with the presence of forest fires in northern Tasmania when ambient temperatures exceed 25 °C. One to two non-woodheater-related exceedences occur each year in the summer months (October–March).

Fig. 3 shows the changes in seasonally averaged PM_{10} concentrations for 1997–2003. This time

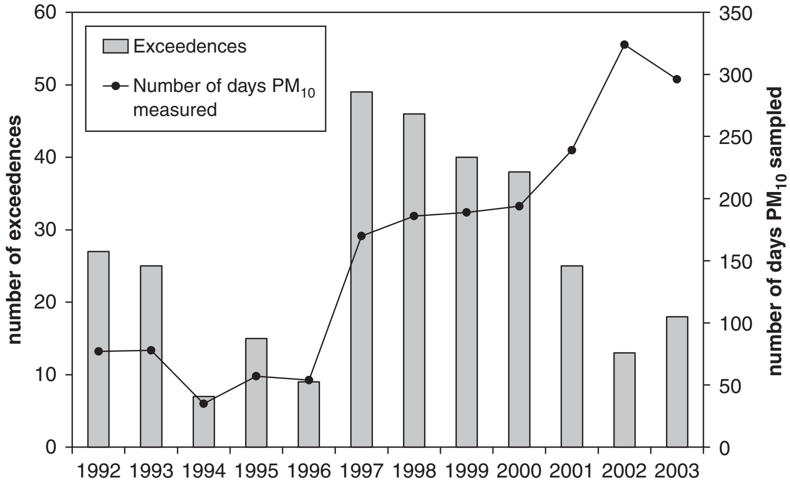

Fig. 2. Trend in PM_{10} exceedences and number of days PM_{10} was measured at the Ti Tree Bend monitoring station. (The number of exceedences in the year 2004 was 10, see Section 3.6.)

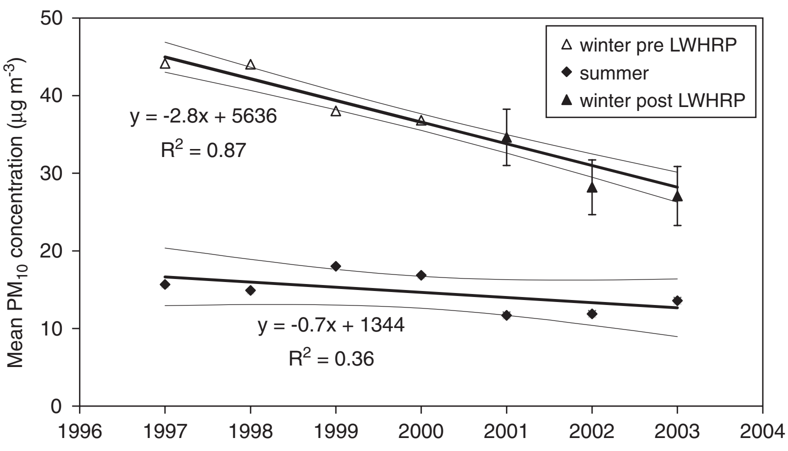

Fig. 3. Seasonally averaged PM_{10} concentrations since 1997, observed at the Ti Tree Bend monitoring station. Winter is May–August and summer is October–April. Linear regressions and 95% confidence intervals to the regression are applied to the summer and pre-LWHRP data. The error bars on the post-LWHRP data represent 95% confidence intervals. The LWHRP commenced in June 2001.

covers the periods both before (1997–2000) and after (2001–2003) the start of the LWHRP. Also shown are the linear regression fits to the summer and winter data and the 95% confidence intervals of these regressions.

During the summer months, the use of woodheaters is minimal, so changes to woodheater numbers should have minimal impact on the summer time PM_{10} concentrations. Fig. 3 shows that since 1997 PM_{10} concentrations during summer have been fairly constant.

A significant rate of decrease in PM_{10} concentrations is observed for the winter-averaged data which is consistent with a decrease in woodheater emissions over the period sampled.

The linear regression line and 95% confidence limits of this line are for the pre-LWHRP data (1997–2000). The regression line is extrapolated to cover the LWHRP period (2002–2003), representing the rate of PM_{10} reduction that would have occurred without the influence of the LWHRP but with an ongoing upgrading and replacement of woodheaters. The mean winter ($\pm$95% confidence) values for the LWRHP years can be compared with the extrapolated pre-LWHRP regression line. The mean winter PM_{10} concentrations for 2002 and 2003 fall below the extrapolated line but within the 95% confidence bounds of the extrapolated pre-LWHRP regression lines. This comparison suggests that the LWHRP may have accelerated the ongoing downward trend in PM_{10} concentrations, but any such effect is not statistically significant in this data.

3. Determination of woodheater carrying capacity

3.1. Modelling tools

TAPM, an air pollution model developed by CSIRO Marine and Atmospheric Research (Hurley, 2002; Hurley et al., 2005; http://www.dar.csiro.au/tapm/), was used to determine the atmospheric carrying capacity of the Launceston airshed for woodheater emissions. TAPM is a three-dimensional (3D), prognostic meteorological and air pollution model, which uses global input databases of terrain height (given at a horizontal resolution of about 250 m for Australia), land use, sea-surface temperature, and Australian Bureau of Meteorology's synoptic-scale meteorology (given at 6-h intervals at approximately 100-km spaced grid points across Australia). The performance of TAPM has been verified in a number of previous studies, e.g. Hurley et al. (2001, 2003, 2005) and Luhar and Hurley (2003).

TAPM (version 2.5) was run with four nested grid domains at 30, 10, 3, 1 km resolution for meteorology (21×21 grid points) and four nested grid domains at 15, 5, 1.5 and 0.5 km for pollution (41×41 grid points), all centred at the location (147°7.5′E, 41°26.5′S), which is equivalent to 510.442 km east and 5412.189 km north in the AMG84 (Australian Map Grid) coordinate system. The outermost meteorological domain covered Tasmania entirely while the innermost domain covered an area of 20 km $\times$ 20 km centred on Launceston. The innermost domain includes nearly all of the woodheater emissions in Launceston. The model default values of the monthly sea-surface temperature and the volumetric deep soil moisture content were used.

Given a gridded emission inventory of woodheater emissions and a background concentration of PM_{10} (see below), TAPM predicts hourly averaged, ground-level PM_{10} concentrations due to woodheater emissions for all grid points within the model domain. The background concentration is then added to the modelled concentrations. At a grid point, a 24-h averaged concentration is calculated from the modelled hourly averaged concentrations, and it is then determined whether it exceeds the Air NEPM of 50 $\mu g\, m^{-3}$.

3.2. Selection of model simulation year

An atmospheric modelling study of Launceston was conducted for a period of 1 year, with woodheaters being the main source of emissions. The 1-year period was considered long enough to account for the seasonal variation of woodheater emissions and local meteorology, but short enough to satisfy computer resource and data processing requirements. Selection of the model year was based on the highest potential for adverse meteorological conditions for woodheater air pollution (as described below) so that the modelled carrying capacity would cover the more extreme pollution occurrences that occur due to inter-annual climatic variations.

Meteorological factors that contribute to the elevated PM_{10} concentrations due to woodheaters include low temperatures and low wind speeds. Low temperatures increase the potential for the formation of nocturnal inversions near the ground, trapping pollutants. Low wind speeds result in poor ventilation of the trapped material. An analysis was performed using the 3-h averaged temperature data and the 3-h scalar-averaged wind-speed data collected at 10 m above the ground at the Australian Bureau of Meteorology's Launceston Airport station (about 12 km south of the city) and the 24-h averaged PM_{10} concentrations measured at Ti Tree Bend for the period 1997–2003. During the winter months, the temperature and wind speed at 1800 Eastern Standard Time (EST) displayed negative correlations ($r \sim -0.6$ and -0.8, respectively) with PM_{10}, suggesting that lower values of these meteorological parameters are linked with higher PM_{10} emissions. The correlation between PM_{10} and the meteorological variables for the summer months was insignificant.

Based on the above, the principal criteria for the selection of a model year were the maximum number of annual cold temperature and low wind-speed events. An analysis of the wind speed and temperature data at the Launceston Airport collected for the years 1992–2003 showed that 1995 and 1998 are the best years to model as they have the highest number of low temperature and low wind-speed occurrences. Because the synoptic meteorological analyses, required as input for TAPM modelling, are available for only 1997 onwards, 1998 was selected as the year to model.

3.3. Calculation of background PM_{10} concentration

A background PM_{10} concentration (i.e. not caused by woodheater emissions) should be added to the modelled concentrations due to woodheater emissions. The likely sources of this background concentration include particulate emissions from sea salt, soil and road dust, motor vehicle exhaust and industrial emissions. The temperature and wind-speed data collected at the Launceston Airport for the period 1997–2003 were analysed. A comparison of the monthly averaged temperature and wind speed (with scalar averaging) at 1800 EST with the monthly averaged PM_{10} showed that that the data fall into two distinct clusters, one with PM_{10} concentrations below $20\,\mu g\,m^{-3}$, corresponding to mid-summer of high temperature and high wind speed, and the other with PM_{10} concentrations greater than $20\,\mu g\,m^{-3}$, corresponding to mid-winter of low temperature and low wind speed, suggesting that temperature and wind speed may be logical criteria for selecting the background PM_{10} concentrations. The low PM_{10} concentration cluster occurred when temperatures were greater than 15 °C and wind speeds were greater than $5\,m\,s^{-1}$, with no forest fires present. Since 1997, there have been 243 such days measured and these data produce an average PM_{10} concentration of $12 \pm 7\,\mu g\,m^{-3}$. Using the temperature criterion means the background PM_{10} concentration are estimated for the summer period; we assume that there is a similar background PM_{10} concentration throughout the year. Therefore, in the following the total PM_{10} concentration is represented by the sum of the background concentration (of $12\,\mu g\,m^{-3}$) and the modelled PM_{10} due to woodheaters.

3.4. PM_{10} emissions from woodheaters in Launceston

A key component of the assessment of the woodheater carrying capacity of Launceston is knowledge of where and at what rate woodheaters emit PM_{10} into the Launceston airshed. Hourly PM_{10} emission rates for each grid cell of the airshed are required for the purpose of transport and diffusion modelling using TAPM, and are calculated using the following spatially and temporally explicit emissions inventory methodology that has been developed for this study.

The emissions inventory is based around available information about woodheating in Launceston, and in Australia, and incorporates a cross check on the amount of wood burnt per household per year for different types of woodheaters. Woodheaters used in Launceston are described by three types: open fires, non-compliant woodheaters and compliant woodheaters. (Woodheaters meeting the Australian Standard for woodheaters (AS/NZS 4013, 1999) will subsequently be described as compliant woodheaters. This Standard limits the maximum allowable particulate emission factor to be 2.25 and $4.0\,g\,kg^{-1}$ for appliances with and without catalytic combustors, respectively, and does not restrict any other emissions.) The firewood used is mostly bluegum (*Eucalyptus globulus*).

Within an inventory grid cell (a $250\,m \times 250\,m$ area of the city's surface), there are n_i number of woodheaters of type i, where the subscript i denotes the type of woodheater (1 = compliant (post-1993) woodheater, 2 = non-compliant (pre-1993) woodheater, and 3 = open fireplace). The quantity n_i divided by the area of the chosen grid cell is the density of woodheaters, $\rho_{w,i}$, within the chosen grid cell.

We assume that there is no day-to-day variation in woodheater use in any given month. In any month m of the year, the fraction of time in a day that woodheaters are utilised for home heating is given by the dimensionless fraction $f_{i,m}$. The woodheater usage during the diurnal cycle, $f_{i,h}$, is the dimensionless fraction that indicates the fraction of the daily woodheater usage $f_{i,m}$ being used in hour h compared with other hours of the day (hence $\sum_{h=0}^{23} f_{i,h} = 1$).

The existing literature (e.g., EA, 2002b) on operation of woodheaters indicates that, in practise, woodheaters are operated to burn wood in three distinct ways: high air flow, low air flow and overloaded wood (smouldering). There is a different wood-burning rate Br, which has dimensions of mass of fuel burnt per unit time, for each heater type for each operating condition. For Launceston, we assumed that all woodheaters are on low flow during the day, high flow during the evening and overloaded during the overnight burn. The literature also indicates that for each heater type for each operating condition (or burning rate) there is a different emission rate E which has dimensions of mass of PM_{10} emissions per unit time, and emission factor Ef, which has dimensions of mass of PM_{10} emissions per mass of fuel burnt. The relationship is $E = \mathrm{Ef} \times \mathrm{Br}$. Thus, the emission factor Ef, and the wood-burning rate Br, are dependant on the hour of day and heater type.

The emissions $E_{i,h,m}$ per unit grid cell due to a woodheater of type i for hour h in month m is given by

$$E_{i,h,m} = n_i f_{i,m} f_{i,h}\, \mathrm{Ef}_{i,h}\, \mathrm{Br}_{i,h}\, H, \tag{1}$$

where $H = 24$. The total emission, E_T, from within a grid cell in one year is

$$E_\mathrm{T} = H \sum_{m=1}^{12} d_m \sum_{h=0}^{23} \sum_{i=1}^{3} n_i f_{i,m} f_{i,h}\, \mathrm{Ef}_{i,h}\, \mathrm{Br}_{i,h}, \tag{2}$$

where d_m is the number of days in month m. The total amount of wood burnt, W_T, within a grid cell during one year is

$$W_\mathrm{T} = H \sum_{m=1}^{12} d_m \sum_{h=0}^{23} \sum_{i=1}^{3} n_i f_{i,m} f_{i,h}\, \mathrm{Br}_{i,h}. \tag{3}$$

Information to populate the parameters in Eqs. (1)–(3) is drawn from the local literature. Responses from a household questionnaire completed by residents in the 58 households with woodheaters studied in the Launceston Personal Exposure Monitoring Study (DEH, 2004) were used to determine the relative hourly usage of compliant and non-compliant woodheaters in a diurnal cycle. There was no appreciable difference between the relative hourly usages of the two types of woodheaters and, therefore, the two were averaged. The resulting diurnal variation of the relative usage ($f_{i,h}$) is presented in Fig. 4, which is similar to that determined as part of an National Pollution Inventory (NPI) study in Launceston (Environmental Protection Authority of Victoria (EPAV), 1996). In Fig. 4, the relative usage for open fireplaces was

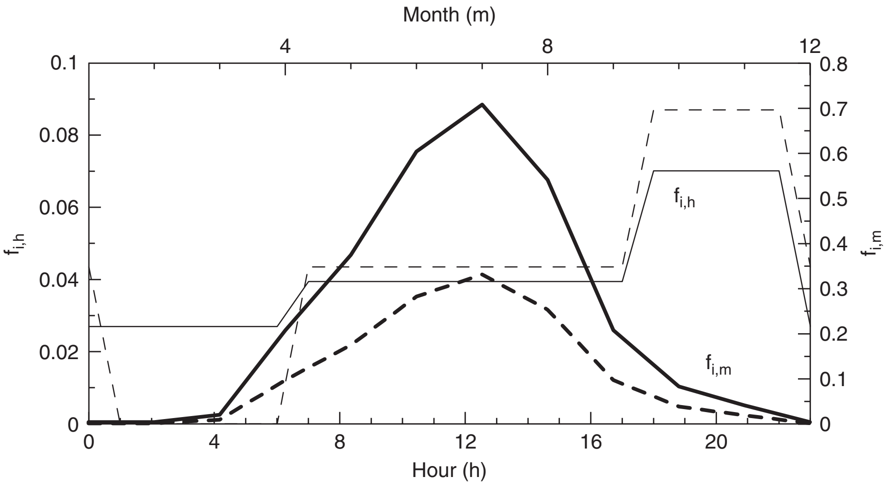

Fig. 4. Diurnal variation of the fractional woodheater usage ($f_{i,h}$) ($\sum_{h=0}^{23} f_{i,h} = 1$), and the monthly variation of $f_{i,m}$—the fraction of time in a day that woodheaters are utilised for home heating. The solid lines are for compliant/non-compliant woodheaters, and the dashed lines are for open fireplaces.

determined using the assumption that open fireplaces were not used between 0100 and 0600 h.

Full monthly or seasonal distributions of woodheater usage were not available for Launceston. A survey for the Hobart region in Tasmania conducted as part of the NPI Hobart Emission Inventory (Power, 2001) presents the mean daily number of wood-burning hours on a seasonal basis. Wood-burning hours for summer, autumn, winter and spring were 0.20, 5.35, 9.60 and 5.35, respectively. The woodheater usage data collected in Launceston (DEH, 2004) indicate that in June 2003 there was a mean daily woodheater usage time of 14.4 h for the compliant and non-compliant woodheaters sampled. Responses to a separate questionnaire (DEH, 2004) indicated a mean average woodheater usage time in winter of 12 h per day in Launceston. Using the above information, and the mass balance requirement for the total wood burnt in a year by a typical compliant/non-compliant woodheater (see below), the average hours of woodheater usage per day in a month were calculated. For open fireplaces these hours were taken to be a constant proportion of the corresponding burn hours in a day for compliant/non-compliant woodheaters. The constant of proportionality was chosen such that it satisfied the mass balance requirement for the total wood burnt in a year by a single open fireplace. Normalisation of burn hours by 24 provided $f_{i,m}$ values, which are plotted in Fig. 4.

The woodheater emissions study reported in EA (2002b) presents fuel burn rates (Br), aerosol (as PM_{10}) emission factors (Ef) and aerosol emission rates (Ef $\times$ Br) for the three types of woodheaters. The fuel burning rates used in the present work based on this study are given in Table 1. The high-flow burn rate (and emission rate discussed later) is assumed to apply to evening burning (1800–2200 h inclusive), the overload burn rate is assumed to apply to overnight burning (2300–0600 h inclusive) and the low burn rate is assumed to apply to daytime burning (0700–1700 h inclusive). The burn rate for an open fireplace is assumed to be constant with the time of the day. Thus, the average daily burn rate for compliant and non-compliant heaters (weighted with the relative usage $f_{i,h}$ in Fig. 4) is calculated to be 2.6 kg h^{-1}. The emission factors for woodheaters adopted for the present study, presented in Table 1, were derived from the information provided by EA (2002a, b), Todd (1997), EPAV (1999) and US Environment Protection Agency (USEPA) (1995). This information gathered here is sufficient to estimate hourly PM_{10} emission rates for any hour of the year for each of the three types of woodheaters in Launceston.

In Launceston, from the above information, the average yearly amount of wood burnt is estimated to be 5.3 tonnes by either a compliant or a non-compliant woodheater, and 3.9 tonnes for an open fireplace. These values can be compared with (a) the annual firewood consumption reported in EA (2001) of 5.1 tonnes for a compliant or non-compliant woodheater, and 3.7 tonnes for an open fireplace, and (b) the estimate for Launceston of a mean annual firewood consumption per wood-burning household of 5.75 tonnes irrespective of the woodheater type (Power, 2001). Thus the burn rates presented in Table 1 are a match to both (a) the product of the observed hourly burn rate times the total annual hours of woodheater use and (b) the total annual firewood consumption values reported in EA (2001).

3.4.1. Spatial distribution of woodheater emissions

To determine the spatial distribution of woodheater emissions in Launceston, the spatial distribution of woodheaters is required. However, such data were not available. As a surrogate, we used the spatial distribution of private dwelling density in Launceston, obtained from the 2001 Australian Bureau of Statistics (ABS) census data for Tasmania. The dwelling density data were gridded at a resolution of 250 m $\times$ 250 m, covering an area of about 14 km $\times$ 17 km, which is an appropriate domain for woodheater emissions for Launceston.

Table 1
Aerosol emission properties adopted for the present study

	Compliant woodheater			Non-compliant woodheater			Open fireplace
Flow conditions	High	Low	Overload	High	Low	Overload	All
Wood burn rate (Br) (kg h^{-1})	3.1	2.3	2.3	3.1	2.3	2.3	4.0
Emission factor (Ef) (g kg^{-1})	1.3	5.2	10.4	2.6	12.2	17.5	17.5

We assumed that the woodheater density (ρ_w) within a grid cell is directly proportional to the dwelling density (ρ_d) within the same grid cell, thus $\rho_w = \alpha\rho_d/100$, where α is the percentage of total dwellings with woodheaters (including open fireplaces) in Launceston. A further assumption was made that the distribution of the dwelling density and the total number of dwellings for 2001 in Launceston were not significantly different from those in 1998 (the model year), and have not changed significantly since then. This is consistent with the small annual rate of replacement of built stock in Launceston.

The percentages of dwellings using woodheaters in Launceston for the years 1992, 1996, 2000 (EA, 2001) and 2004 (Murray Pavia, 2004, EnergyConsult Pty Ltd., personal communication) are 66%, 60%, 46% and 30%, respectively, and are plotted (as diamonds) in Fig. 5. It is apparent that since 1992 the percentage of dwellings using woodheaters has decreased almost linearly with time. For the model year 1998, the percentage (α) of dwellings using woodheaters calculated from the least-squares fit (solid line) in Fig. 5 is 53%.

As well as the total woodheater numbers, there is the need for information of the proportion of woodheaters in each class, compliant and non-compliant woodheaters and open fireplaces. Based on the available information, the following respective figures were derived: 37.4%, 56.2%, and 6.4% for the year 1996 (Power, 2001; personal communication, 2005); 49.5%, 40% and 10.5% for the year

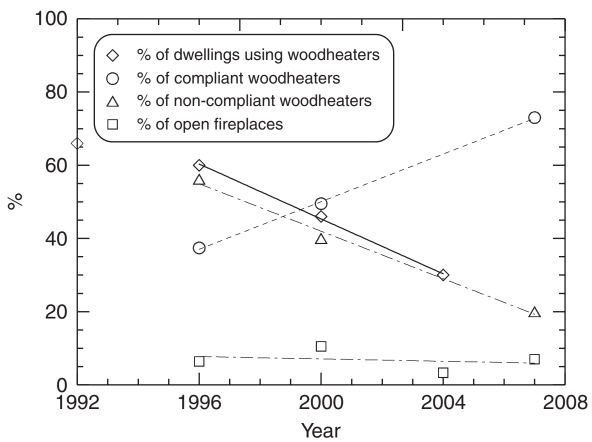

Fig. 5. Annual variation of: the percentage of dwellings using woodheaters (◇), the percentage of compliant woodheaters (○), the percentage of non-compliant woodheaters (△), and the percentage of open fireplaces (□) in Launceston. The lines are linear least-squares fits to the data.

2000 (EA, 2001); and 73%, 20% and 7% for the year 2007 (projected) (EA, 2001). The proportion of open fireplaces for the year 2004 was 3.3% (Murray Pavia, 2004, EnergyConsult Pty Ltd., personal communication). These data are presented in Fig. 5 along with linear least-squares fits. We estimated that in the year 1998 the proportions of compliant woodheaters, non-compliant woodheaters and open fireplaces were 45.7%, 46.8% and 7.5%, respectively. The density of woodheaters of category i ($= 1, 2, 3$), therefore, is

$$\rho_{w,i} = \alpha\beta_i\rho_d/(100 \times 100), \tag{4}$$

where β_i is the percentage of woodheaters of category i.

Eq. (1), together with the data given above, was used to calculate the PM_{10} emission rate ($\mathrm{g\,h^{-1}}$) within each grid cell of size $250\,\mathrm{m} \times 250\,\mathrm{m}$ for each woodheater type and for each hour in the year 1998. Similarly, using the values of the emission factors, burn rates, seasonal and diurnal variations, and the woodheater distribution calculated below, the total emission of PM_{10} due to woodheaters in Launceston was determined to be 506 tonnes for the year 2000, which is lower than the value of 609 tonnes reported in EA (2001). Such difference is not unexpected given the uncertainties in the parameters (e.g. emission factors) used to derive the emissions (see also Section 3.6).

The spatial distribution of the total PM_{10} emissions due to the three types of woodheaters in Launceston for the year 1998 is shown in Fig. 6. Similarly, the emissions for other years can be calculated using the least-squares fits shown in Fig. 5. The structure of the emissions field reflects the topography with the Tamar River flowing through the centre of the valley.

Although PM_{10} is considered as fine particles, the bulk (~80%) of it in winter in Launceston is the even finer $PM_{2.5}$ (particulate matter with an aerodynamic diameter of 2.5 μm or less) (Ayers et al., 1999). For such a fine particle mix, the model results with and without the use of the gravitational settling and deposition option in the model are virtually the same within the spatial domain considered here. We neglect any decay or secondary generation of particulate matter, and treat PM_{10} essentially as a tracer within the modelling domain. TAPM was run with three tracers, corresponding to the three types of woodheater emissions, so that the influence of any changes in the woodheater proportions on the modelled concentrations could be

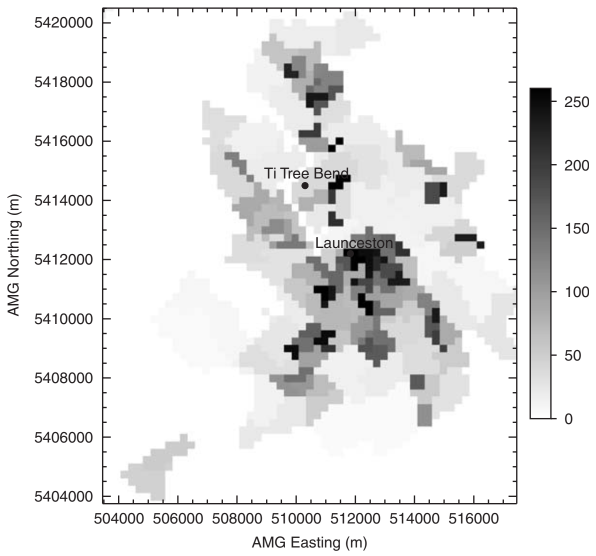

Fig. 6. The distribution of total PM_{10} emissions ($kg\,ha^{-1}$) due to woodheaters in Launceston for the year 2000. Also shown are the Ti Tree Bend monitoring station and the centre of Launceston.

assessed by appropriately scaling the three tracer concentrations obtained from the model and then summing them up to obtain the total concentration.

3.5. Modelling results

3.5.1. Comparison of surface meteorology

Before comparing the model predictions of PM_{10} concentrations with the measurements and estimating woodheater carrying capacity, it is instructive to examine whether the model is appropriately simulating the local meteorology governing air pollution transport and diffusion in the area. Fig. 7 shows observed and TAPM predicted wind roses close to the surface at the Launceston Airport Station for the year 1998. Because the Airport location does not lie within the innermost model meteorological domain (which is 20 km × 20 km centred on Launceston, with a resolution of 1 km), the surface meteorological estimates at the location corresponding to the Airport location in the next outer model domain (60 km × 60 km with a coarser resolution of 3 km) were used for comparison. The airport meteorological data are given at a frequency of every 3 h, and the corresponding data were extracted from the model output (the sample size (N) was 2916). The resolution of the wind speed and wind direction observations was rather coarse, at $0.5\,m\,s^{-1}$ and 10°, respectively. The two wind roses in Fig. 7 show a reasonable degree of agreement. The dominant observed wind direction is NNW, whereas the modelled one is NW. TAPM shows a tendency to overestimate the lower wind speeds, but underestimates the higher ones. A statistical analysis shows that for wind speed the correlation coefficient (r) is 0.75, the index of agreement (IOA) is 0.86 (1 is perfect), the slope of the linear reduced-major-axis (RMA)[1] fit (Davis, 1986) is 0.88, and the intercept of the fit is $0.74\,m\,s^{-1}$. (Note that unlike r, IOA is sensitive to differences between the observed and model means as well as to certain changes in proportionality (Willmott, 1981).)

A comparison between the 3-h modelled and measured ambient temperatures at the Launceston Airport Station indicated a good performance by TAPM. The correlation coefficient (r) was 0.91, the IOA was 0.94, the slope of the linear RMA fit was 1.10, and the intercept of the fit was $-2\,°C$.

Overall, the model meteorology is in fairly good agreement with the data, and the model performs slightly better for the summer period than for the winter period.

3.6. Woodheater carrying capacity for PM_{10}

The 24-h averaged PM_{10} concentrations due to the three types of woodheaters were extracted from the model output for the innermost pollution domain for the year 1998, and were summed up to obtain total concentrations. A background concentration of $12\,\mu g\,m^{-3}$ (see Section 3.3) was added to these model concentrations. Due to local variations in PM_{10} estimates caused by coarse resolution of the model (i.e. 0.5 km for pollution and 1 km for meteorology), the assumed woodheater distribution, and the input synoptic meteorology, the modelled PM_{10} concentrations within the grid cells closest to the Ti Tree Bend location (AMG 510.3 km East; 5414.5 km North) were examined, and the grid cell that most closely represented the observed PM_{10} concentrations was selected for a detailed comparison with the data. This grid cell was 1 km east of the Ti Tree Bend site.

It was found necessary to multiply an empirical correction factor of 1.2 to the modelled concentrations, for which there may be a number of possible reasons. Firstly, using the values of the emission

[1]The RMA method rather than the least-squares fitting method is used when both sets of data (i.e. measurements (x) and modelled (y) values here) are subject to errors and neither can be regarded as a function of the other.

factors, burn rates, seasonal and diurnal variations, and the woodheater distribution calculated above, the total emission of PM_{10} due to woodheaters in Launceston is determined to be 506 tonnes for the year 2000, which is lower than 609 tonnes reported in EA (2001); the latter is a factor of 1.2 higher. Secondly, both the sources and the receptors in the model are specified in terms of gridded volumes, each of size 500 m × 500 m × 10 m near the ground, whereas in reality these are point locations. Consequently, it may be expected that the modelled concentrations will show a smaller variance in PM_{10} concentrations, with lower concentrations in the upper part of the distribution, than the observations because the model has this volume averaging.

Fig. 8 shows the time series of the observed and modelled 24-h averaged PM_{10} concentrations for the year 1998 at Ti Tree Bend (sample size $N = 186$). The model estimates above 50 μg m^{-3} are in agreement with the observation; however, the spread of the estimated concentration distribution is narrower than observed. In addition, the model does not estimate observed concentrations below the average background level of 12 μg m^{-3} added to the model values. Some of the observed concentrations were below the background concentration in the winter–spring period, which are most likely due to the fact that the background value is really a distribution, determined earlier to be 12 ± 7 μg m^{-3} and therefore will include values lower than 12 μg m^{-3}. The highest modelled concentration for Ti Tree Bend was 129.7 μg m^{-3} and the number of exceedences was 55. These figures show good agreement with the measured peak of 123.7 μg m^{-3} and 46 exceedences.

The scatter plot between the observed and modelled concentrations in Fig. 9a suggests that although there is a large spread of the data points around the line of perfect fit (i.e. the $y = x$ line), the model values are in reasonable agreement with the data, as shown by a correlation coefficient (r) of 0.69 and an IOA of 0.81. The lines representing the RMA and the linear least-squares fit are also shown in Fig. 9a.

Fig. 9b presents a quantile–quantile (q–q) plot of the predicted versus observed PM_{10} concentrations. A q–q plot is used for determining if two datasets with equal sample size (i.e. observed and predicted concentrations here) come from populations with a common distribution, and is essentially a plot of the sorted predicted concentrations (i.e. irrespective of time) against the sorted observed concentrations. If the two sets come from a population with the same distribution, the points should fall approximately along the 1:1 reference line. The greater the departure from this reference line, the greater the evidence for the conclusion that the two data sets have come from populations with different distributions. It is apparent from Fig. 9b that the model is capable of simulating the observed PM_{10} concentration distribution very well, with a slight overprediction for the observed concentrations less than about 50 μg m^{-3} and a slight underprediction for the concentrations at the top-end of the distribution.

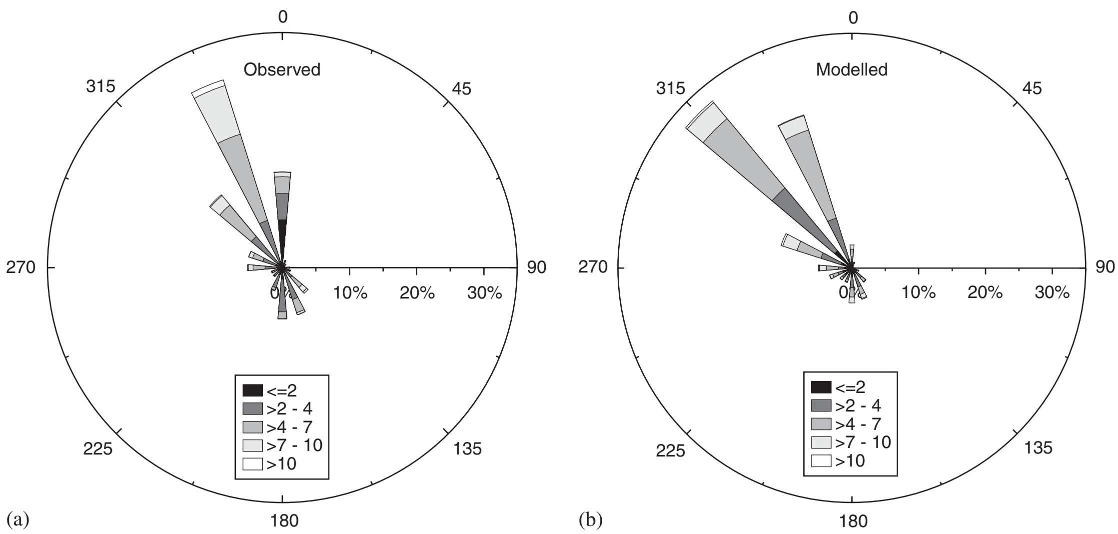

Fig. 7. (a) Observed and (b) TAPM predicted wind roses near the surface at the Launceston Airport Station for the year 1998 based on 3-h wind speed (m s^{-1}) and wind direction values ($N = 2916$).

It is worth investigating the dominant atmospheric factors that lead to high ground level concentration in Launceston. The Tamar Valley is oriented in a NW–SE direction and is bounded by ridges and hills on both sides that range from 100 to 400 m above sea level. The model results show that high concentrations are typically observed in the night when the woodheater emissions are high and when nocturnal drainage winds (formed under clear-sky inversion conditions) from the valley sidewalls flow downslope in the NE and SW directions and converge, leading to a build-up of polluted air within the lower depths of the valley. Fig. 10 presents such a situation at 0100 h on 13

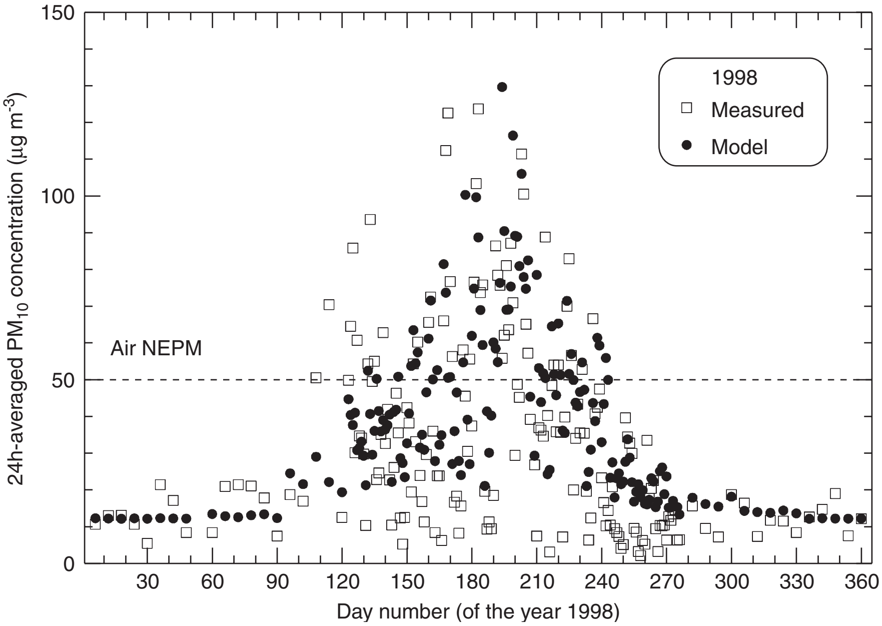

Fig. 8. Time series of the observed and modelled 24-h averaged PM_{10} concentration at the Ti Tree Bend monitoring station for the year 1998. The dashed line represents the Air NEPM limit of $50\,\mu g\,m^{-3}$ ($N = 186$).

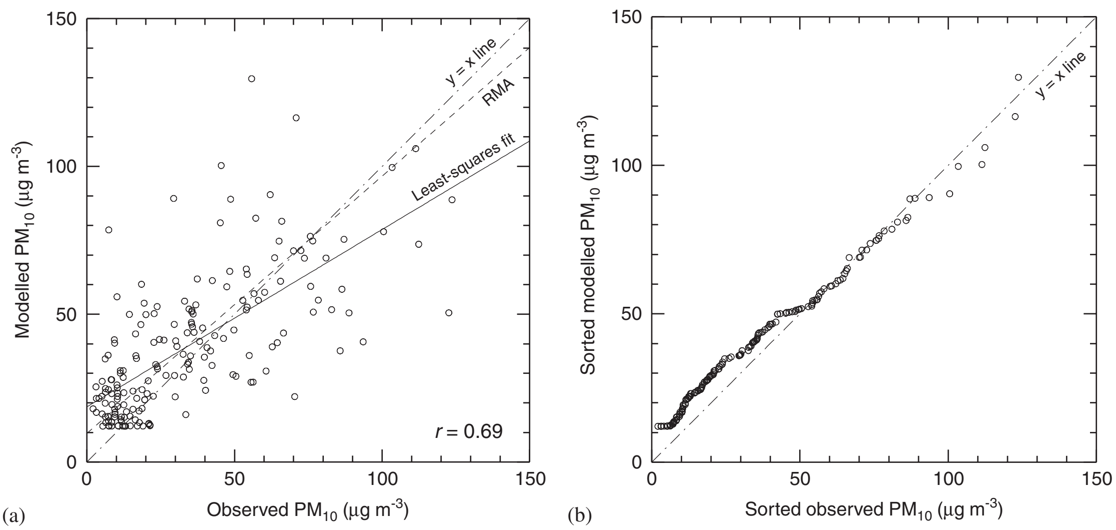

Fig. 9. (a) Scatter plot and (b) quantile–quantile (q–q) plot of the predicted versus observed 24-h averaged PM_{10} concentrations at the Ti Tree Bend monitoring station for the year 1998 ($N = 186$).

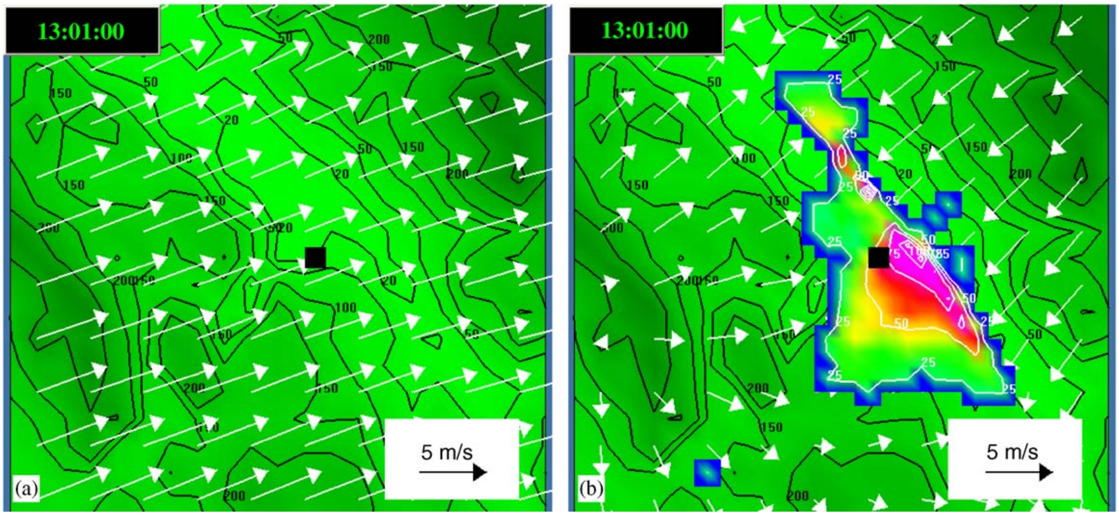

Fig. 10. Hourly averaged modelled wind and PM_{10} concentration fields at 0100 h on 13 July 1998 at (a) 500 m AGL and (b) 10 m AGL. The grid domain is 20 km × 20 km. The solid square in the centre represents the city centre. The black lines are the topographical contours (metres above mean sea level). The concentration contours are given for values 25, 50, 75, 100 and 125 $\mu g\,m^{-3}$. There are no significant concentrations at 500 m AGL.

July; the modelled upper-air flow at 500 m above the ground level (AGL) is from WSW with no significant modelled PM_{10} concentration at this level (Fig. 10a), whereas the flow at 10 m AGL (Fig. 10b) clearly shows the opposing NE and SW drainage winds and how they confine the plume due to woodheater emissions near the ground. The modelling results in Fig. 10 are consistent with the meteorological measurements made by Low et al. (1989) using tethered balloon soundings in September–October 1982 in the lower Tamar Valley, about 35 km northwest of Launceston, which showed that the wind field was influenced by the local NE, SW drainage flows in the early morning in the lower level, and by the synoptic scale winds above 200 m.

Given the good performance of TAPM in simulating the PM_{10} data for the year 1998, the model was used to assess the influence of the year-to-year changes in the woodheater numbers and the proportions of woodheater types on PM_{10} concentrations in Launceston. Using the trends in the numbers of woodheaters presented in Section 3.4.1 and assuming that the dwelling density distribution does not change with time, scaling factors that represent ratios of woodheater emissions for the years 1997 and 1999–2009 to those for the year 1998 were determined. These scaling factors were then applied to the model PM_{10} concentrations calculated for the year 1998 to determine the concentrations for the other years. We assumed that the model meteorology for the year 1998, which we assessed to be an adverse year for pollution dispersion, is applicable to the other years for the purpose of determining the number of exceedences for the calculation of the woodheater carrying capacity of Launceston.

Fig. 11 compares the number of the PM_{10} exceedences determined from the model concentrations with the observed exceedences at Ti Tree Bend as a function of time. There is a good agreement between the model curve and the data. Note that the value of the number of exceedences observed for the year 2004, which are all due to woodheaters, was obtained from http://www.launceston.tas.gov.au/subsector.php?id=2447 (also Michael Groth, 2005, Department of Primary Industries, Water and Environment, personal communication) after much of the modelling and analysis reported in this paper was completed. The maximum number of exceedences in a year allowed by the Air NEPM is five. We assumed that, on average, there are one or two PM_{10} exceedences during summer in a given year. Therefore, the target for the maximum number of exceedences allowed for woodheater emissions in Launceston is three or four. According to Fig. 11, if the woodheater numbers and proportions follow the trends derived in this paper, and assuming that the PM_{10} background concentration and the woodheater emission factors do not change from year to year, the number of PM_{10} exceedences

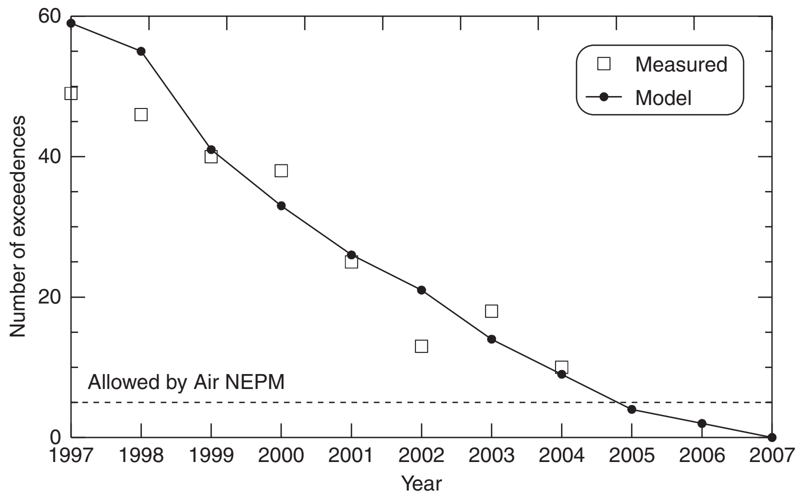

Fig. 11. Comparison of the number of exceedences of the PM_{10} Air NEPM determined from the modelled concentrations with the observed number at the Ti Tree Bend monitoring station.

at Ti Tree Bend would meet the target number of exceedences (i.e. three to four) in the year 2006, with less exceedences in subsequent years. According to the trends discussed earlier, in the year 2006, the total number of woodheaters would be 23% of the total number of dwellings, of which the compliant, non-compliant and open-fireplace woodheater proportions are 73%, 21% and 6%, respectively.

However, compliance with the Air NEPM standard for PM_{10} at Ti Tree Bend does not mean that the standard would be met at all locations in Launceston. Our modelling results allow an examination of the spatial distribution of the estimated concentration and the locations of areas of high PM_{10} concentration. From this information the number of woodheaters and the proportion of the types of woodheaters that are required to meet the Air NEPM requirements in these areas of high PM_{10} concentration can be calculated. The location where the model estimates the maximum 24-averaged PM_{10} concentrations and the highest number of exceedences within the model domain, was about 3.5 km southeast of the Ti Tree Bend Station. We assumed that complying with the Air NEPM requirements at this site would result in the NEPM goal being met for all areas in the Launceston city. A model curve similar to that in Fig. 11 for this site (not presented here) shows that with the continuation of the present trends the Air NEPM goal will be met by the year 2007. For the year 2007, the total number of woodheaters would be 20% of the total number of dwellings, of which 76%, 18%, 6% would be compliant woodheaters, non-compliant woodheaters and open fireplaces, respectively. Thus, the woodheater carrying capacity of Launceston is estimated to be 20% of the total number of dwellings, with the woodheater number dominated by the compliant woodheaters (76%).

4. Conclusions

In Launceston (Australia), frequent exceedences of the Air NEPM standard for PM_{10} occur as a result of woodheater use in the winter. An analysis of PM_{10} data observed at the Ti Tree Bend monitoring station in Launceston indicates a decrease in the number of annual PM_{10} exceedences since 1997, with perhaps some acceleration in this decrease resulting from the implementation of the Launceston Woodheater Replacement Programme (LWHRP) in mid-2001.

Meteorological observations taken at the Launceston Airport, together with the observed PM_{10} concentrations, were analysed, and a criterion developed in terms of wind speed and temperature values that indicates the absence, or minimal contribution, of woodheater emissions. This analysis was applied to the available data, and indicates a background concentration of PM_{10} of $12\,\mu g\,m^{-3}$ which was added to the modelled PM_{10} levels.

An air pollution model called TAPM was selected as the modelling tool to determine the woodheater carrying capacity in Launceston—the number of woodheaters that can operate in Launceston without exceeding the Air NEPM standard for PM_{10}, which allows 5 daily exceedences in a year. The year 1998 was chosen as the year to model since the meteorological conditions for this year were most conducive to poor pollution dispersion. Gridded woodheater emissions of PM_{10} required in TAPM were derived by assuming that the woodheater density within a grid cell is directly proportional to the dwelling density in that grid cell. The woodheater emission rates, the diurnal and seasonal variations in their usages, the percentage of dwellings with woodheaters, and the proportions of compliant/non-compliant woodheaters and open fireplaces (and their trends) were estimated using existing information.

The model surface meteorology (wind speed and temperature) showed reasonable agreement with the measurements.

The highest 24-h averaged PM_{10} concentration and the number of exceedences of the Air NEPM predicted by TAPM for the year 1998 were in agreement with the measurements at Ti Tree Bend. The maximum modelled concentrations occurred at a site about 3.5 km southeast of Ti Tree Bend, so that meeting Air NEPM requirements at that site meant that Air NEPM requirements would likely be met for the entire Launceston area. Allowing for one to two summertime exceedences of PM_{10} concentrations due to non-woodheater sources, the model results indicated that the PM_{10} Air NEPM would be met anywhere in Launceston (assuming typical meteorological conditions and no significant change in dwelling density and background concentration from the levels used here) when the total number of woodheaters is 20% of the total number of dwellings, of which 76%, 18%, 6% would be compliant woodheaters, non-compliant woodheaters and open fireplaces, respectively. With the present trends in the regional woodheater profile, this should occur in the year 2007. Thus, the woodheater carrying capacity of Launceston with regard to PM_{10} exceedences is 20% of the total number of dwellings, with the woodheater number dominated by the compliant woodheaters (76%).

Although there are uncertainties in the above model estimates of carrying capacity and exceedences, they do serve as a quantitative guide for policy support. The main data deficiencies in Launceston with regard to woodheaters and air quality (in terms of PM_{10}) are: the actual particle emissions rates from woodheaters in the city and surrounding region, and the number of residences with woodheaters, the type of woodheater (compliant, non-compliant and open fireplaces) and the spatial distribution of these woodheaters.

Acknowledgements

This study was funded by the Department of the Environment and Heritage (DEH), Australia, and we thank Khokan Bagchi of the DEH for his assistance. Thanks are also due to Mike Power and Michael Groth for providing the PM_{10} data, to Rosemary Norwood for information on woodheaters, to Ian Barnes-Keoghan for the meteorological data, and to Mick Meyer for information on emission factors. Mike Power also supplied information on census data and woodheater emissions. Two anonymous referees provided useful comments.

References

AS/NZS 4013, 1999. Domestic solid fuel burning appliances—method for determination of flue gas emission. Australian/New Zealand Standard AS/NZ 4013, 1999, Standards Association of Australia, Homebush, NSW, Australia, Standards New Zealand, Wellington, New Zealand, p. 22.

Ayers, G.P., Keywood, M.D., Gras, J.L., Cohen, D., Garton, D., Bailey, G.M., 1999. Chemical and physical properties of Australian fine particles: a pilot study. Final Report from CSIRO and ANSTO to Environment Australia. Available at: ⟨http://www.cmar.csiro.au/e-print/open/CSIRO_AFP.pdf⟩.

Davis, J.C., 1986. Statistics and Data Analysis in Geology. Wiley, New York, p. 646.

Department of Environment and Heritage (DEH), 2004. Technical Report No. 8: Personal Monitoring of Selected VOCs: The Contribution of Woodsmoke to Exposure. A study by CSIRO Atmospheric Research, p. 75. Available at: ⟨http://www.deh.gov.au/atmosphere/airquality/publications/pem/index.html⟩.

Environment Australia (EA), 2001. Woodheater emissions management: program for the Tamar Valley—scoping study. Submitted to Environment Australia by Atech Group, May 2001, p. 94. Available at: ⟨http://www.deh.gov.au/atmosphere/airquality/publications/tamar/⟩.

Environment Australia (EA), 2002a. Technical Report No. 4: Review of Literature on Residential Firewood Use, Wood-Smoke and Air Toxics. Canberra, Australia. Consultancy by CSIRO Atmospheric Research, authors: Gras, J.L., Meyer, C.P., Weeks, I.A., Gillett, R.W., Galbally, I., Todd, J., Carnovale, F., Joynt R., Hinwood, A., Berko, H., Brown, S., p. 109. Available at: ⟨http://www.deh.gov.au/atmosphere/airquality/publications/report4/index.html⟩.

Environment Australia (EA), 2002b. Technical Report No. 5: Emissions from Domestic Solid Fuel Burning Appliances. Canberra, Australia. Consultancy by CSIRO Atmospheric Research authors: Gras, J.L., Meyer, C.P., Weeks, I.A.,

Gillett, R.W., Galbally, I.E., Todd, J., Carnovale, F., Joynt, R., Hinwood, A., Berko, H., Brown, S., p. 95 + appendices. Available at: ⟨http://www.deh.gov.au/atmosphere/airquality/publications/report5/index.html⟩.
Environmental Protection Authority of Victoria (EPAV), 1996. Technical Report on the Air Emissions Trials for the National Pollution Inventory – On Emissions Estimation and Dispersion Modelling, vol. 2. Australian Government Publishing Service (AGPS), Canberra, Australia.
Environmental Protection Authority of Victoria (EPAV), 1999. Emission Estimation Technique Manual for Aggregated Emissions from Domestic Solid Fuel Burning. Australian Government Publishing Service (AGPS), Canberra, Australia. Available at: ⟨http://www.npi.gov.au/handbooks/aedmanuals/solidfuel_rev2.html⟩.
Hurley, P., 2002. The air pollution model (TAPM) version 2. Part 1: Technical description. Australia. CSIRO Atmospheric Research. Technical Paper No. 55. p. 49. Available at: ⟨http://www.dar.csiro.au/tapm/⟩.
Hurley, P.J., Blockley, A., Rayner, K., 2001. Verification of a prognostic meteorological and air pollution model for year-long predictions in the Kwinana region of Western Australia. Atmospheric Environment 35, 1871–1880.
Hurley, P., Manins, P., Lee, S., Boyle, R., Ng, Y.L., Dewundege, P., 2003. Year-long, hi-resolution, urban airshed modelling: verification of TAPM predictions of smog and particles in Melbourne, Australia. Atmospheric Environment 37, 1899–1910.
Hurley, P.J., Physick, W.L., Luhar, A.K., 2005. TAPM: a practical approach to prognostic meteorological and air pollution modelling. Environmental Modelling and Software 20, 737–752.
Kesby, P., Bagchi, K., Carnovale, F., Abernethy, I., 2002. Improving Launceston's air—a collaborative approach to reducing woodheater emissions. In: Proceedings of the 16th International Clean Air and Environment Conference, Clean Air Society of Australia & New Zealand.
Low, P.S., Moriarty, W.W., Todd, J.J., 1989. Complex air flows in the Lower Tamar Valley, Tasmania: some observations. Atmospheric Environment 23, 1925–1938.
Luhar, A.K., Hurley, P.J., 2003. Evaluation of TAPM, a prognostic meteorological and air pollution model, using urban and rural point-source data. Atmospheric Environment 37, 2795–2810.
National Environment Protection Council (NEPC), 1998. National Environment Protection Measure and Revised Impact Statement for the Ambient Air Quality. NEPC, Adelaide, Australia.
Power, M., 2001. Air pollution dispersion within the Tamar Valley. Ph.D. Thesis, University of Tasmania, p. 402.
Todd, J.J., 1997. Impact of pollution controls on woodheater emission factors. In-House Fuelwood Report 59, Centre for Environmental Studies, University of Tasmania, Hobart, Australia.
US Environment Protection Agency (USEPA), 1995. AP-42 Compilation of Air Pollutant Emission Factors, vol. 1: Stationary Point and Area Sources, Fifth Edition. Available at: ⟨http://www.epa.gov/ttn/chief/ap42/ch01/final/c01s09.pdf⟩.
Willmott, C.J., 1981. On the validation of models. Physical Geography 2, 184–194.