

# Straight-Line Paths and Urban Airshed Modelling

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# Executive Summary

This report demonstrates methodologies for using predictive airshed models as tools in the determination of straight-line paths (SLiPs) to compliance with the National Environmental Standards (NES). It is shown that the relationship between PM<sub>10</sub> concentration and emission rate can be considered linear, and this relationship is exploited to make predictions of future PM<sub>10</sub> levels under prescribed emissions reduction scenarios. This may be done without further computer-intensive modelling beyond a base-case simulation of present-day conditions.

The specific examples considered here use The Air Pollution Model (TAPM) which is a self-contained PC-based model capable of long-term (seasonal to annual) runs in just a few days of processing. The only additional data inputs needed are the sources of air pollutants, taken from emissions inventories. Local meteorological data are optional, but it is strongly recommended that they be used where available, as part of the model validation process (and optionally as model inputs).

Numerical experiments have been carried out using the Hawke's Bay region, Masterton, Christchurch and Blenheim as specific case studies. The detailed methodology varies slightly for each, but all use the model to predict emissions reductions needed to decrease the number of exceedences of the NES for PM<sub>10</sub> to a maximum of one occasion per year. This is the target for 2013 under the NES.

This research focuses on PM<sub>10</sub> directly emitted by domestic heating with pollution events occurring in calm, stable, wintertime conditions. It is a challenge for any meteorological model to simulate such conditions and ways of improving TAPM's performance are suggested. Also, extensions of the methodology to regions dominated by other source-types (for instance motor vehicles or industry) are discussed.

The approach taken here can not be guaranteed to be successful. Indeed, for at least one of the cases presented, it has not been. Reasons for this must be investigated in future research:

- (a) PM<sub>10</sub> exceedences occur under extreme meteorological conditions, which are difficult for models to reproduce (and the highest PM<sub>10</sub> levels are under-estimated);
- (b) The exceedences may occur under conditions of 'unusual' emissions. The current modelling approach uses the same emissions each day, with variability in PM<sub>10</sub> levels coming from variability in the meteorology. There may be no observed relationship between PM<sub>10</sub> and meteorology, in which case, the model cannot be expected to produce realistic PM<sub>10</sub> concentrations matching the observed day-to-day variability. In any case, model runs should include at least the seasons during which exceedences occur (better, a full year, or several years) long to reproduce this statistically;
- (c) Region-specific emissions inventories may be unavailable.

Further extensions of these methods will also attempt to account for contributions from secondary particulates and natural sources.

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## Introduction

### National Environmental Standards and Straight-line Paths

The National Environmental Standards (NES) were developed by the Ministry for the Environment and their approval announced by the Minister on 15 July 2004. The new regulations came into effect on 6 September 2004. The Standards themselves come into effect at different times, those for ambient air quality on 1 September 2005. For more information, see

<http://www.mfe.govt.nz/laws/standards/>,

<http://www.beehive.govt.nz/ViewDocument.aspx?DocumentID=20332>,

<http://gpacts.knowledge-basket.co.nz/regs/regs/text/2004/2004309.txt>,

<http://www.mfe.govt.nz/laws/standards/ambient-air-quality-standards-table.html>, and

<http://www.mfe.govt.nz/laws/standards/amendments.html>.

A users' guide (UG) for the implementation of the Standards was produced in November 2004 (MfE, 2004). The Standard for ambient PM<sub>10</sub> is a 24-hour-average concentration of 50 µg m<sup>-3</sup> to be exceeded no more than once per year (UG section 3.2). This regulation applies everywhere people are exposed.

Regions must be divided into 'airsheds' (UG section 3.3 and 3.3.1), to be advised by local government, in which the regulations are to be applied. These are not airsheds in the geophysical sense; rather, they are linked to air-quality management policy, and have been denoted Local Air quality Management Areas (LAMAs). In effect, ambient PM<sub>10</sub> may exceed 50 µg m<sup>-3</sup> no more than once in each LAMA. They will be gazetted in time for the regulations to come into force by 1 September 2005. This process is underway, with LAMAs defined for the whole country by Fisher *et al.* (2005). This is based on estimated PM<sub>10</sub> emissions, meteorological and topographical effects, and current observations of PM<sub>10</sub> where available. The LAMAs defined using these methods have been used by many local government authorities as a basis for their own determination of LAMAs; the work of Fisher *et al.* (2005) provides a scientific basis, upon which adjustments have been made locally to account for political boundaries within regions, for instance.

There are many airsheds currently not in compliance with the NES (and these have been labelled Category 1 LAMAs by Fisher *et al.* (2005)). Compliance must be achieved by the year 2013, and the concept of the 'straight-line path' (SLiP)<sup>#</sup> provides targets for air quality in the interim (UG section 3.3.1). Essentially, the current state of air quality must approach NES compliance at least linearly – i.e. at any time in the interim, air quality must be better than that defined by the straight line. The current state of air quality can be described by the annual number of PM<sub>10</sub> exceedences, which must decrease to only one by 2013, and be halfway there by 2009, three-quarters by 2011, etc. This has significant consequences for resource consents, which will not be granted in a particular airshed if more than one exceedence in future years would result.

Pollution mitigation options designed to attain NES in currently non-compliant airsheds depend on reduction of emissions and a prediction of the effects on concentration levels in the future. For this, predictive models are needed. Validated models are acknowledged to be an element of an effective air quality management framework (UG section 3.8) and may be used to predict spatial patterns of dispersion, short- and long-term impacts, and provide a more comprehensive understanding of air quality processes.

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<sup>#</sup> The amendments to NES include an updated Regulation 17 which allows for the use of a 'curved-line path' (CLiP) where this is included in a Regional Plan. The methodologies and modelling techniques described in this report need only be slightly adapted for CLiPs.

Specifically, this report describes some uses of numerical models as

- (a) additional tools in LAMA definition, providing a link between concentrations and emissions (through meteorological and topographical effects);
- (b) predictors of future air quality as emissions change, to assess progress along the SLiP.

This research is being carried out as part of a Foundation for Research, Science and Technology programme *Protecting New Zealand's Clean Air* (contract CO1X0405), which includes regional-scale dispersion modelling as one of its sub-projects. Others deal with emissions inventory development and air quality monitoring, and the modelling links closely to these – emissions are a key input, and model results must be validated against measurements at climate and air quality monitoring sites.

## Concentration / Emission Relationships: Uses of Urban Airshed Models

By way of example, the report describes the application of so-called urban airshed models to several regions in New Zealand. Airshed models simulate the meteorology, and dispersion of emitted pollutants from all sources in an area of interest. Restricting the analysis to PM<sub>10</sub>, treating it as a chemically-inert tracer, it is clear that there is a linear relationship between concentration and emissions. For instance, halving emissions results in halving of concentrations, etc. Concentrations and emissions are linked through pollution dispersion processes, which depend on the meteorology. Put simply,

$$\text{Modelled PM}_{10} \text{ Concentration} = (\text{Source Factor}) \times (\text{Meteorological Factor})$$

This generic relationship does not need to specify time, location or averaging period (but these are implicitly there); it merely points out the linearity in the relationship. The *Meteorological Factor* is provided by the airshed model; the *Source Factor* is a direct input to the model. Emissions may be partitioned according to source-type, and the contribution to concentration from each source type calculated separately by the model. Then

$$\text{Modelled PM}_{10} (\text{Source Y}) = (\text{Source Factor for Source Y}) \\ \times (\text{Meteorological Factor for Source Y})$$

and

$$\text{Total Modelled PM}_{10} \text{ Concentration} = \text{Sum of Modelled PM}_{10} \text{ due to each Source}$$

The modelled *Meteorological Factor* is different for each source, as the sources may be in differing locations or their emissions occurring at different times of the day. For instance, emissions from motor vehicles may occur during the day with peaks morning and evening, but emissions from domestic fires occur during the evening and night-time.

Airshed models are computationally expensive to run. Expressing the concentration-emissions relationship as above shows that the model need be run only once to calculate the meteorological factors for each source-type. Then, to calculate the effects of pollution mitigation options, the emissions factors need merely to be rescaled. The modelled PM<sub>10</sub> for each source may then be recalculated without re-running the airshed model. **This is a powerful shortcut.** The model calculates PM<sub>10</sub> concentrations every hour at all locations, complementing air quality observations which may be 24-hour averages at a few sites measured every three days. Provided the model results are validated where observations are made, the model may be used to calculate the state of air quality anywhere else.

Knowing the distribution of modelled daily PM<sub>10</sub> concentrations, the number of NES exceedences may be calculated for any rescaling of (*any of*) the *Source Factors*. The main aim of this report is to show using predictive models how emissions need to be reduced to gradually approach (along the SLiP) compliance with NES in the future. It is not the purpose of the report to suggest policy options which should be implemented – such decisions will be made by local government.

Several examples are presented in the following sections, as a demonstration of the concepts and methodologies which may be used. They are not presented as the definitive solutions for the regions considered – these are being addressed in collaboration with the relevant local authorities.

## Urban Airshed Modelling Results for SLiPs

This section contains a summary of the main results for each region. Modelling results are being reported on more fully elsewhere in cooperation with specific Regional Councils (Gimson, 2005; Xie and Gimson, 2005).

## The Air Pollution Model (TAPM)

The model used in the following examples is CSIRO's TAPM (see Hurley *et al.* (2005)), version 3. TAPM calculates the local meteorology based on the laws of atmospheric dynamics (in the same way that weather forecasts are produced). Local meteorological data are therefore not needed, but may be 'assimilated' into the model runs and/or used to validate the model performance. A good simulation of the meteorology is crucial to a good simulation of the dispersion of air pollutants.

The model operates on a series of nested grids, increasing in resolution, with the coarsest usually covering most of New Zealand, and the finest covering the region of interest (the Regional Council area). The finest horizontal resolution is typically a cell-size of 1 km × 1 km. On each meteorological grid, pollutants are emitted and dispersed by the modelled winds and turbulence. In TAPM, the dispersion may be carried out on a higher-resolution grid (with correspondingly more cells, as it covers the same area). The necessity to do this depends on the spatial scales of importance in the dispersion, and it allows a higher-resolution dispersion run without the large increase in computational time that would be needed for more detailed meteorology. For the examples of Hawke's Bay, Masterton and Blenheim dispersion modelling is carried out at double the meteorology resolution, to a cell-size of 500 m × 500 m on the finest grid.

LAMAs have been defined based on estimated patterns of emissions and observations of PM<sub>10</sub> by Fisher *et al.* (2005), and emissions estimates will be used in due course to create a National Pollutant Emissions Inventory for New Zealand. The GIS-based inventory includes industry emissions (point sources), domestic and vehicle emissions (presented as averages over each census area unit (CAU)). Domestic emissions include those from coal and wood burning in winter. Vehicle emissions consider on-road vehicles only, but account for tailpipe, break wear, tyre wear and dust re-suspension. The CAU-based emissions estimates are interpolated onto a regular grid coinciding with the dispersion model grid.

There are two important issues associated with airshed modelling, which must be stated at the outset:

- 1) The model must be validated under present-day conditions for each case before it may be used to predict effects under proposed future conditions;
- 2) A significant amount of skill, time and effort is required from the modeller to achieve this. The model is not a 'black box', and several configurations may need to be tested before satisfactory results are achieved. **In this respect, the following results are provisional – this report presents a methodology for the calculation of straight-line paths, rather than finalized calculations of straight-line paths themselves.**

## Example 1: The Hawke's Bay Region

TAPM has been applied to the Hawke's Bay region to simulate dispersion of PM<sub>10</sub> during the winter of 2004. The high-resolution domain covers the urban areas of Napier, Hastings and Havelock North, and the surrounding hills.

### Observations

During winter 2004 there were two exceedences at the air quality monitoring sites at Nelson Park, Napier. A statistical relationship exists between 24-hour-averaged PM<sub>10</sub> and the 24-hour-averaged wind speed (as a scalar) at Napier airport, with correlation 0.86. A linear regression of observed PM<sub>10</sub> on the reciprocal of the wind speed reproduces the exceedences observed in July 2004 (though not as severely) and predicts five more in the period of observations (June to September 2004) on days measurements were not made (see Figure 1).

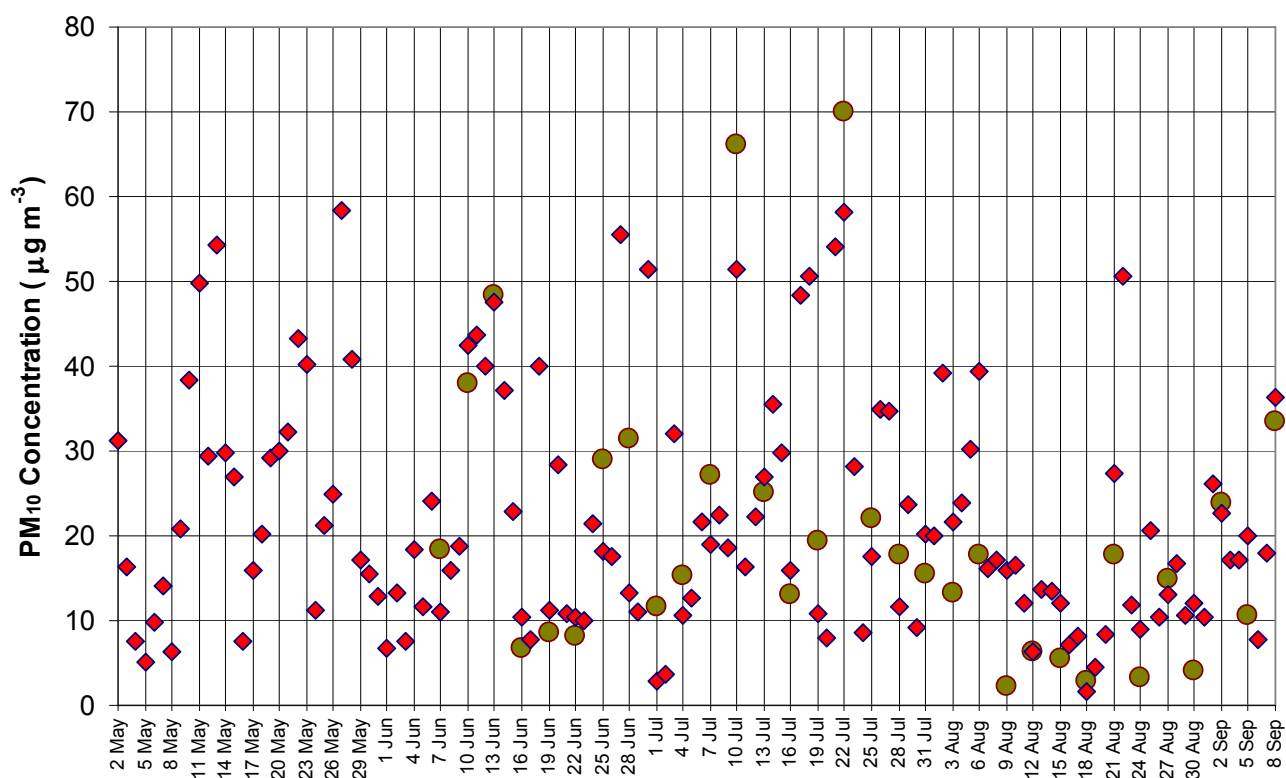
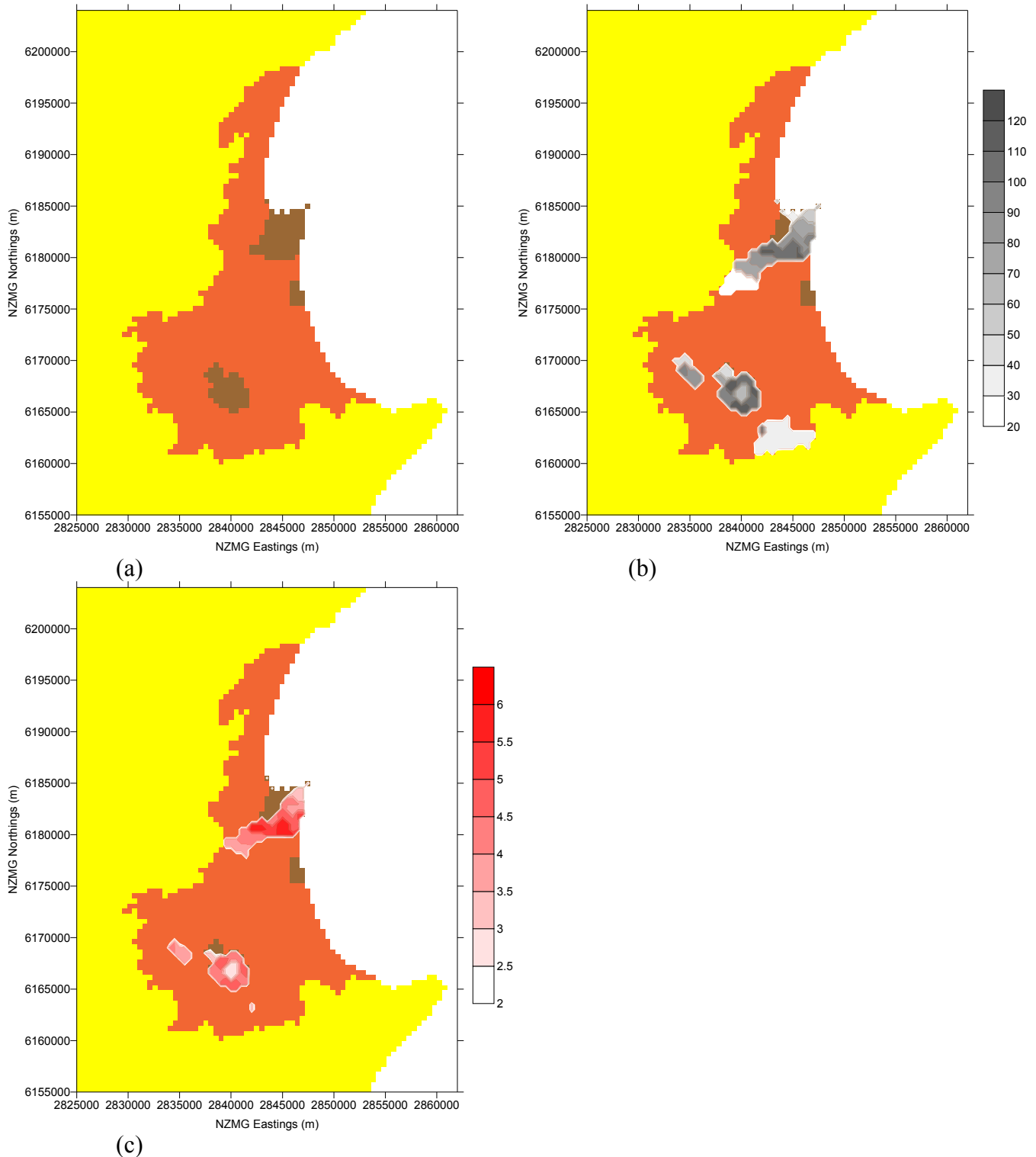


Figure 1 24-hour average PM<sub>10</sub> concentration at Nelson Park; observed (green circles – every three days) and obtained through linear regression (red diamonds - daily). The x-axis labels refer to 00:00 (NZST) at the end of each 24-hour observing period, so the labelled date is subsequent to the day of the observation.

### Model Configuration

TAPM is run on four nested grids, with horizontal resolution 30 km, 10 km, 3 km and 1 km, each containing 30 × 36 grid-cells. Three-dimensional hourly meteorological fields are calculated on these grids, which consist of 25 levels in the vertical. The lowest level is 10 m above ground level (AGL), then 25 m AGL, increasing in vertical spacing and stretching to a total depth of 8 km. The model simulation runs from 1 May 2004 to 9 September 2004, and wind data from Napier airport and Whakatapu are assimilated into the run.

Dispersion modelling is carried out on each meteorological grid, but at double the resolution. Hence for dispersion there are  $60 \times 72$  cells, with resolution 500 m on the finest grid. A specific inventory has been developed for the Hawke's Bay region using a more robust methodology, and these latest emissions estimates are used as model inputs (Wilton, 2005). Emissions are divided into several source-types – including domestic heating, motor vehicles, industry and outdoor burning. CAU-based daily emission rates are interpolated to the 500 m grid, and shown in Figure 2.



**Figure 2 LAMA categories and emissions inventory. (a) LAMA categories (yellow=3, orange=2, brown=1, white=sea); superposed (b) domestic heating emissions ( $\text{kg km}^{-2} \text{day}^{-1}$ ) and (c) motor vehicles (same units). Note the emissions colour scales cover different ranges, and do not extend downward to zero emissions.**



PM<sub>10</sub> is dispersed as an inert tracer in TAPM. The model allows four tracers to be run simultaneously. These are chosen to be

- 1) PM<sub>10</sub> emitted by domestic fires in category 1 LAMAs;
- 2) PM<sub>10</sub> emitted by domestic fires in other categories of LAMA;
- 3) PM<sub>10</sub> emitted by motor vehicles in all LAMAs;
- 4) All other emissions of PM<sub>10</sub> in the inventory (including industrial emissions and outdoor burning).

Temporal profiles of emissions must be defined for the model, so that a realistic fraction of the daily total is released each hour. For tracers 1 and 2, a home heating profile is used, whereby most PM<sub>10</sub> is released during the evening, between 5 pm and midnight. For tracer 3, emissions peak by 9 am, remain elevated – but at a lower level – during the day, peak at 6 pm and decrease during the night. For tracer 4, emissions are roughly constant through the 24-hour period.

### Model Results

A statistical comparison of wind, temperature and humidity is shown in Table 1, between model results and observations at Napier airport, Whakatu and Bridge Pa. For wind speed, the model results are good – this is helped by the assimilation of data at the airport and Whakatu. Good model skill (SK\_R less than 1 and SK\_V close to 1) is shown at all sites for wind and temperature, with the exception SK\_R for the wind speed at Bridge Pa. The error (RMSE) is almost as high as the observed variability (SD), due to an underestimate of wind speed by the model at this location. This could be due to the effects of wind data assimilation at the other sites, where the wind speed is observed to be lower. Relative humidity results are not good at any of the sites – it is significantly underestimated, and does not correlate well either. (This is not investigated further, as it has little effect on pollution dispersion).

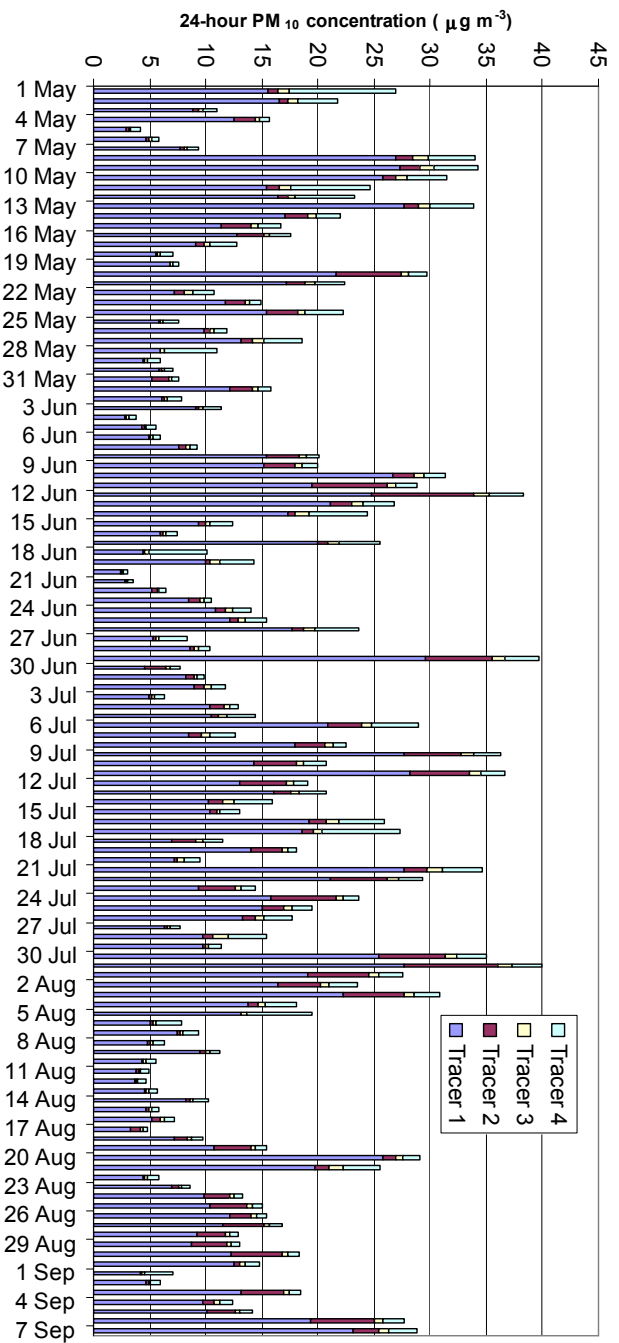
**Table 1 TAPM meteorological model performance statistics. Columns are site/parameter (S/P), number of observations (No. Obs.), mean observed (Obs. AV), standard deviation of observed (Obs. SD), mean modelled (Mod. AV), standard deviation of modelled (Mod. SD), root-mean-square error (RMSE), skill scores SK\_R (RMSE/Obs SD) and SK\_V (Mod SD/Obs SD), and correlation  $\rho$ . To show model skill, SK\_R should be much less than 1, and SK\_V should be around 1. Units are m s<sup>-1</sup> for wind speed (WS, as a scalar); °C for temperature (T) and % for relative humidity (RH).**

S/P	No. Obs.	Obs. AV	Obs. SD	Mod. AV	Mod. SD	RMSE	SK_R	SK_V	$\rho$
<b>Napier (WS)</b>	3120	3.8	2.7	3.8	2.0	1.6	0.57	0.74	0.83
<b>Whakatu (WS)</b>	3114	3.2	2.4	3.5	2.1	1.2	0.48	0.87	0.88
<b>Bridge Pa (WS)</b>	3104	4.4	1.9	3.4	2.0	1.8	0.95	1.04	0.71
<b>Napier (T)</b>	3120	10.2	4.3	9.6	4.1	2.5	0.57	0.94	0.84
<b>Whakatu (T)</b>	2709	8.2	4.7	9.2	4.3	2.9	0.61	0.90	0.82
<b>Bridge Pa (T)</b>	3104	9.4	5.1	8.4	4.7	3.0	0.59	0.92	0.83
<b>Napier (RH)</b>	3120	75	16	58	11	23	1.47	0.67	0.39
<b>Whakatu (RH)</b>	2709	81	16	65	11	21	1.32	0.70	0.51
<b>Bridge Pa (RH)</b>	3104	83	16	63	13	25	1.55	0.80	0.47

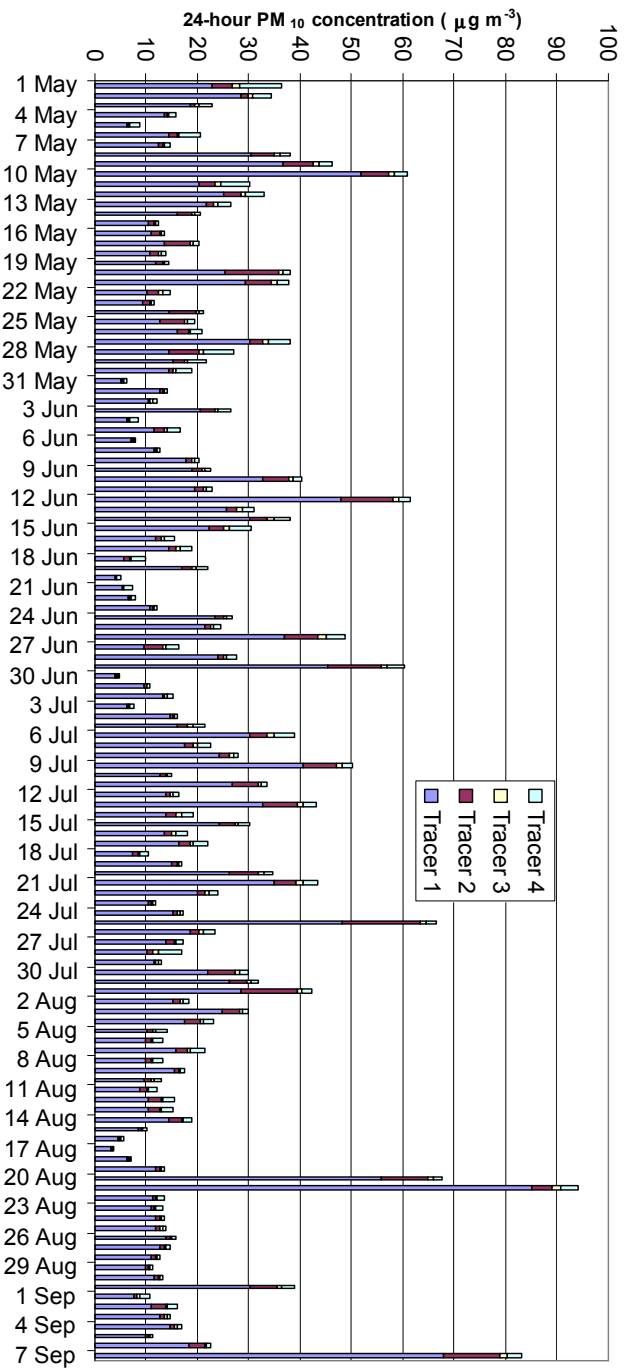
Note that the statistical comparison gives an indication of the general model skill in estimating the meteorological conditions. Of specific importance for pollution events is the model's ability to simulate stable, low-wind conditions.

Daily PM<sub>10</sub> levels as modelled by TAPM are shown in Figure 3 at the air quality monitoring sites. Both sites are in category 1 LAMAs and, as expected, the major contribution to PM<sub>10</sub> is from the category 1 areas themselves (i.e. tracer 1). There are often significant contributions from LAMAs of category 2 or 3 (tracer 2), and from other

sources (tracer 4, but these are highly uncertain). Contributions from motor vehicles sources (tracer 3) are negligible.



(a) Nelson Park, Napier.

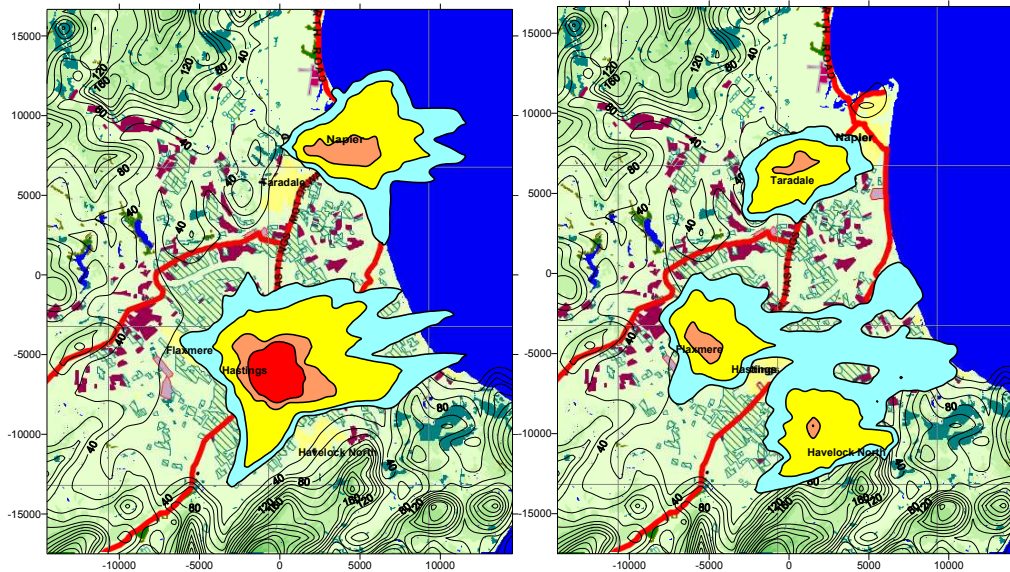


(b) St John College, Hastings.

Figure 3 Modelled 24-hour average PM<sub>10</sub>-classified according to tracer number (matching the source-type as described in the text). (a) Nelson Park, Napier; (b) St John College, Hastings. (Note the differing vertical axes).

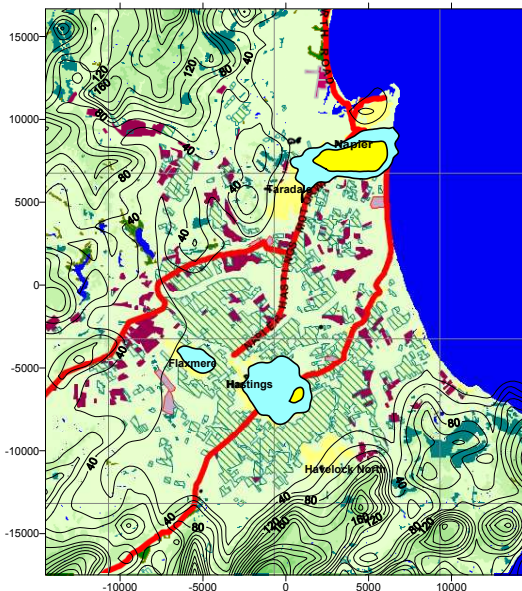
## Maximum PM<sub>10</sub> Concentrations and the Straight-Line Path to NES Compliance

Maps of the maximum modelled concentrations from PM<sub>10</sub> tracers 1, 2 and 3 are shown in Figure 4. Emissions from domestic heating in category 1 LAMAs show plumes of PM<sub>10</sub> over Napier and Hastings (Figure 4(a)). Higher concentrations are modelled over Hastings, exceeding 50  $\mu\text{g m}^{-3}$ , although observations show exceedences occur over Napier also – the modelling confirms that both should be category 1 LAMAs, and shows the area over which exceedences can extend. Note the spatial complexity in the pollutant plumes – this is driven by complex wind fields simulated in model, which are determined by topographical effects. The south eastern edge of the Hastings plume follows the terrain contours.



(a) PM<sub>10</sub> from domestic emissions in category 1 LAMAs

(b) PM<sub>10</sub> from domestic emissions in other LAMAs



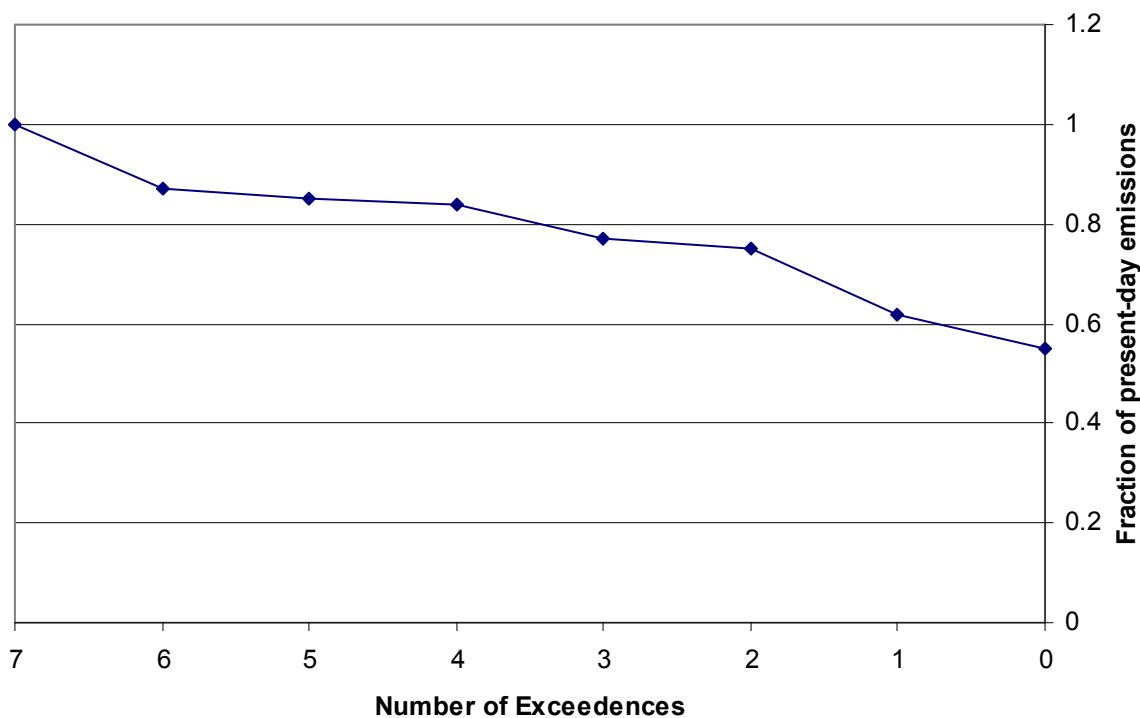
(c) PM<sub>10</sub> from motor vehicle emissions (x10)

**Figure 4 Maximum modelled 24-hour PM<sub>10</sub> concentrations over the period 1 May – 7 September 2004 in  $\mu\text{g m}^{-3}$ . Shading is according to environmental performance indicator (EPI) category; blue {12, 16} (“good”), yellow {16, 33} (“acceptable”); orange {33, 50} (“alert”); red (> 50, “exceedence”). The motor vehicle component is scaled up by a factor of 10. Unfilled contours are of model terrain height.**

Plumes from domestic heating in category 2 and 3 LAMAs are shown in Figure 4(b). The modelling indicates concentrations are just as high over Taradale, Flaxmere and Havelock North as they are in Napier. The maximum PM<sub>10</sub> just reaches 50 µg m<sup>-3</sup> over Havelock North, indicating that this area should be a category 1 LAMA. For the other areas, the modelling is not as conclusive. PM<sub>10</sub> levels are as high as Napier, indicating Taradale and Flaxmere should be in the same category as Napier (category 1). However, the model does not produce exceedences of the PM<sub>10</sub> standard in any of these locations.

Contributions to PM<sub>10</sub> levels from motor vehicle emissions appear to be negligible (they are scaled up by a factor of ten in Figure 4(c)). However, emissions are averaged over grid-cell areas in the model, when in reality they are confined to city streets as line sources. Near the roadside, a higher contribution to PM<sub>10</sub> from vehicles would be observed, but TAPM is not the right kind of model to simulate dispersion at this scale.

The PM<sub>10</sub> concentration at St John College is considered in the calculation of the straight-line path (although the location of maximum PM<sub>10</sub> in a composite total from Figure 4 could be chosen). Emission components from domestic heating and motor vehicles may be varied independently. Also, high modelled concentrations at St John College have a significant component from domestic heating in surrounding areas (category 2 LAMAs, see Figure 3(b)), so emissions of tracer 1 and 2 (both domestic) may also be varied independently. This can be done as the model results comprise a daily PM<sub>10</sub> concentration at all grid-cells, broken down according to source-type. The modelled components of PM<sub>10</sub> are linear in the emissions of that component.



**Figure 5 Emissions changes required to reduce the number of PM<sub>10</sub> exceedences (per year).**

Considering the modelled PM<sub>10</sub> at St John College as comprising tracers 1, 2 and 3 (domestic heating (two components) and motor vehicles), there are 7 exceedences in the winter 2004 period. The emissions reductions required to decrease the number of exceedences linearly – through reducing domestic and vehicle emissions by the same fraction – are shown in Figure 5. The aim may be a reduction of one exceedence per year, in which case the x-axis would start at 2004 (7 exceedences) and end at 2010 (one exceedence) or 2011 (no exceedences). The decrease in emissions is not linear due to the non-uniform distribution of daily concentrations, but ends at around 60% of present-day emissions when there would be one exceedence at St John College.

It is more realistic to not change vehicle emissions, and consider reductions in emissions of tracers 1 and 2 separately. Then, tracers 1 and 2 need to be both reduced by the same amount as shown in Figure 5 (around

40%), as tracer 3 is a small component of the total modelled PM<sub>10</sub>. Reducing only tracer 1 by that amount also reduces the number of exceedences to 1. In other words, although several of the exceedences at St John College (in a category 1 LAMA) would not occur if there were no contribution from emissions in the surrounding (category 2) LAMAs, removal of all exceedences can only occur by reducing emissions in the category 1 LAMA (by 40%), regardless of what occurs in the surrounding LAMAs and regardless of any reductions in vehicle emissions which might occur.

## Example 2: Masterton

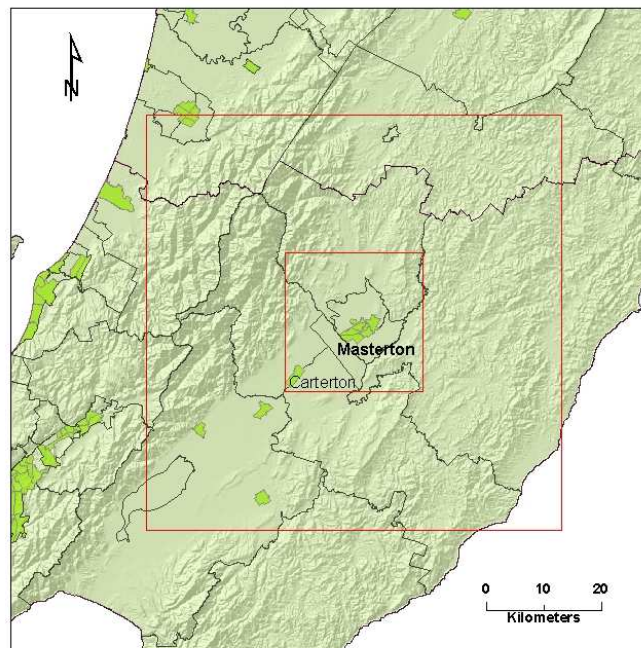
TAPM has been applied to the Wairarapa region to simulate dispersion of PM<sub>10</sub> during the winter of 2003. The high-resolution domain covers the urban areas of Masterton and Carterton, and surrounding terrain.

### Introduction and Model Configuration

Masterton, with an urban population of about 18,000, located on the flat river plain of the Wairarapa valley, suffers poor air quality at times in winter due to emissions of particulates from domestic heating (Davy, 2003). Air quality monitoring shows 24-hour PM<sub>10</sub> exceedences of 50 µg m<sup>-3</sup> in the urban area. Therefore, some reductions in emissions are required for NES compliance in 2013.

TAPM was run for the winter months May to August, 2003. The centre of the model domain is shown in Figure 6. Four grids of increasing resolution are used, telescoping down to Masterton town centre. Each meteorological grid has 25×25 points in the horizontal, with resolution of 30, 10, 3 and 1 km. The corresponding dispersion model grids cover the same areas but at twice the resolution, the finest grid at a 500 m cell size. The grid structure in the vertical is the same as that used for Hawke's Bay example. A deep soil-moisture content of 0.25 kg kg<sup>-1</sup> was used for May, and 0.3 kg kg<sup>-1</sup> for June to August. Default values of the other parameters were used, along with standard microphysics options.

Domestic, vehicle and industry sources account for 80%, 17% and 3% of PM<sub>10</sub> emissions respectively. CAUs with high domestic PM<sub>10</sub> emissions (>10 kg/day/km<sup>2</sup>) are highlighted in Figure 6. PM<sub>10</sub> is treated as an inert tracer in the model runs, which include a background concentration of 10 µg m<sup>-3</sup>.



**Figure 6 TAPM model domain (centre: 175°38'E, 40°56.5'S) for Masterton with nested grids 3 and 4 displayed. CAUs with high domestic PM<sub>10</sub> emissions (>10 kg/day/km<sup>2</sup>) are shaded in dark green.**

The Masterton ambient air quality monitoring site at Wairarapa College and the East Taratahi meteorological site are located in the finest model grid (grid 4, marked on Figure 8). Hourly PM<sub>10</sub> concentrations (from TEOM), wind speed, wind direction and temperature were measured at the Masterton site (Davy, 2003). Hourly wind speed, wind direction and temperature data at East Taratahi (also marked on Figure 8) were obtained from the national climate database (CLIDB).

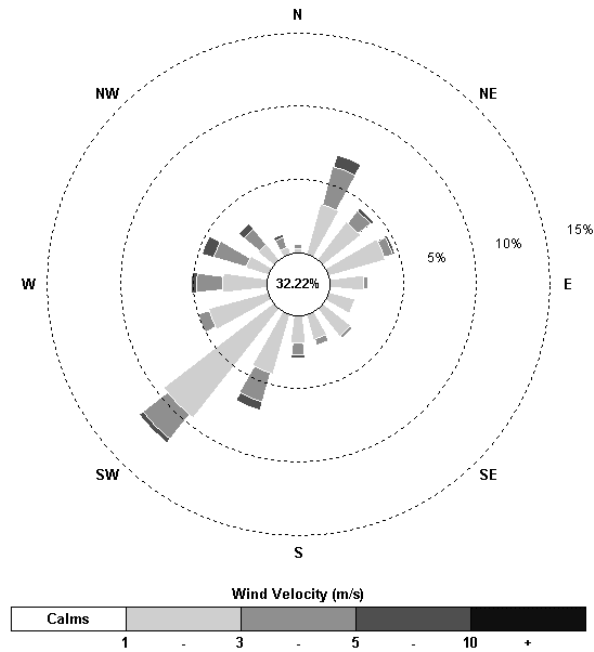
## Results

To assess the effect on dispersion of the assimilation of wind observed at Masterton and East Taratahi, model runs were carried out both with and without data assimilation.

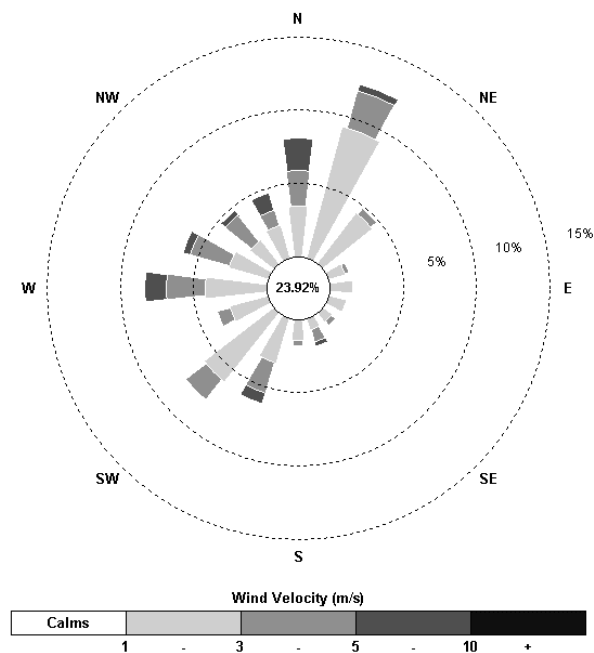
The performance statistics, when compared with hourly wind speed, wind direction and temperature observations, and 24-hour moving-average PM<sub>10</sub> measurements, are shown in Table 2. Simulated wind speed agrees well with observations for both Masterton and East Taratahi sites with IOA values greater than 0.7, although the model tends to over-estimate the mean wind speed. Assimilation of wind data improves the modelled wind speed, leading to IOA values greater than 0.9 for both sites. Results for temperature were excellent for both sites with IOA values greater than 0.85. There is some change in temperature due to wind data assimilation, although temperature data themselves are not assimilated into the model run.

**Table 2 Model performance statistics for the Masterton winter 2003 runs. These include the index of agreement (IOA), which is a better indicator of model performance than the correlation (Willmott, 1982). It varies between 0 (no agreement) and 1 (perfect agreement), with agreement generally considered ‘acceptable’ if the IOA is greater than 0.6. Subscripts \_A for wind data assimilation and \_NA for no wind data assimilation.**

Variable	No_Obs	Mean_Obs	Mean_Mod	Std_Obs	Std_Mod	$\rho$	RMSE	IOA	SK_V	SK_R
<b>Wind speed (m s<sup>-1</sup>)</b>										
Masterton_NA	2952	1.9	3.1	1.4	1.6	0.65	1.74	0.71	1.08	1.20
Masterton_A	2952	1.9	2.2	1.4	1.6	0.86	0.89	0.91	1.12	0.62
East Taratahi_NA	2951	2.8	3.4	2.3	1.8	0.63	1.93	0.76	0.77	0.84
East Taratahi_A	2951	2.8	3.0	2.3	1.9	0.84	1.26	0.91	0.85	0.55
<b>Temperature (degC)</b>										
Masterton_NA	2950	9.4	9.1	4.4	3.3	0.86	2.31	0.90	0.74	0.53
Masterton_A	2950	9.4	9.4	4.4	3.1	0.86	2.32	0.90	0.71	0.53
East Taratahi_NA	2951	8.6	8.4	5.1	3.8	0.88	2.55	0.91	0.75	0.50
East Taratahi_A	2951	8.6	9.4	5.1	3.1	0.86	3.00	0.86	0.61	0.59



(a) Wind rose from observations at Masterton.



(b) Modelled wind rose at Masterton.

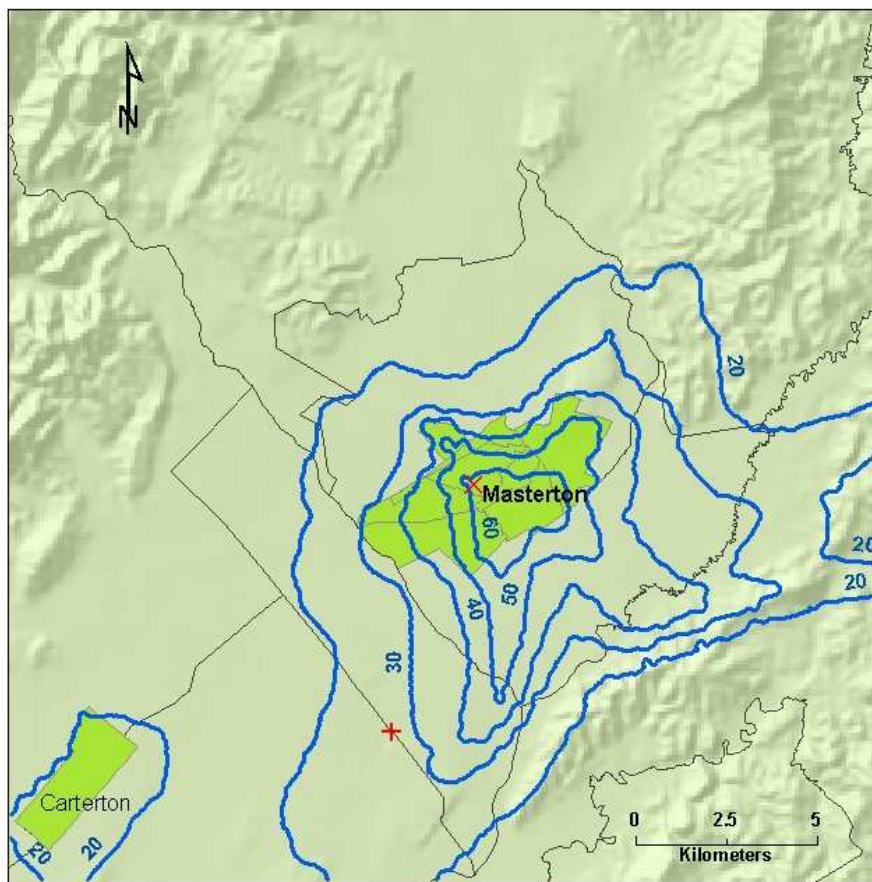
**Figure 7 Wind roses of observed and modelled data for the Masterton monitoring site for May-August, 2003.**

Figure 7 shows wind roses constructed from the observed and modelled data at Masterton. Model outputs with the assimilation option simulate the southwesterly and northeasterly winds, the two most common flows, reasonably well, better than those from the without assimilation run (not shown). At East Taratahi, the wind roses for the observed and modelled data (not shown) demonstrate similar characteristics as at Masterton. Assimilation also improves results for calm conditions ( $<1$  m/s). The fraction of calm periods are 32.22% and 9.76 % at Masterton

and East Taratahi respectively, compared to modelled 23.92 % (with assimilation) and 5.89 % (without assimilation) at Masterton, and 11.89 % (with assimilation) and 5.28 % (without assimilation) at East Taratahi.

These results expose a general difficulty of prognostic meteorological models in simulating calm periods, and show that one way of improving this aspect is to assimilate wind observations into the model runs.

Maximum 24-hour PM<sub>10</sub> concentrations on the 0.5 km grid are presented in Figure 8. High concentrations coincide with high domestic PM<sub>10</sub> sources and exceedence areas cover much of the Masterton urban region.



**Figure 8 Spatial distribution of maximum 24-hour PM<sub>10</sub> concentrations (in µg m<sup>-3</sup>) on the 500 m grid. The Masterton ambient monitoring site at Wairarapa College (x) and the East Taratahi meteorological site (+) are also displayed. CAUs with high domestic PM<sub>10</sub> emissions (greater than 10 kg/day/km<sup>2</sup>) are shaded in dark green.**

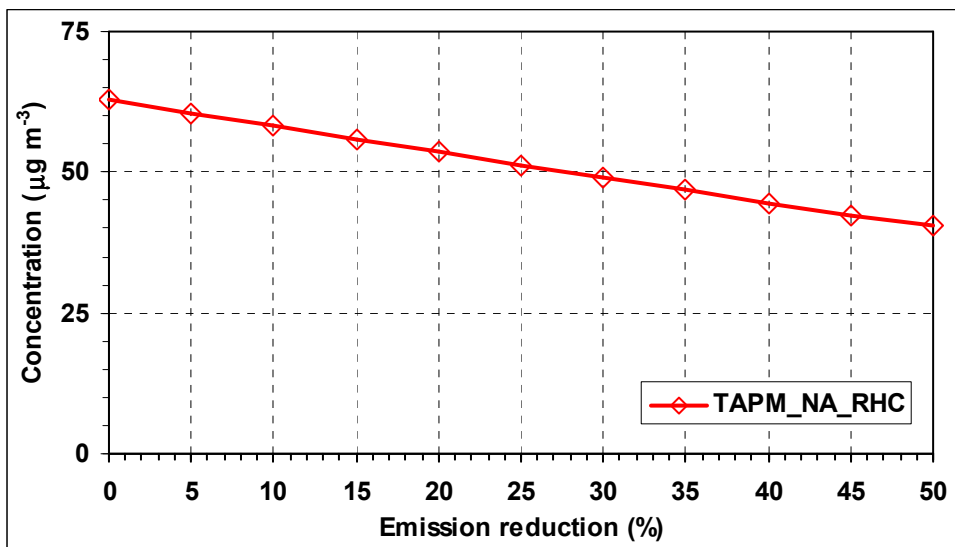
### Emissions Reduction Scenarios

The Wairarapa region contains Category 1, 2 and 3 LAMAs. In category 1 areas (the highlighted CAUs in Figure 8), PM<sub>10</sub> exceedences currently occur, or are likely to occur if no mitigation action is taken. In category 2 and 3 areas, PM<sub>10</sub> concentrations are currently or likely to be below 50 µg m<sup>-3</sup>. It is anticipated that only Category 1 LAMAs will require regulatory attention. As emissions are primarily from domestic heating, pollution mitigation options would focus on this source-type. It is beyond the scope of this work to suggest what those options might be – however, the model can be used to assess their effects.

In Masterton, domestic PM<sub>10</sub> emissions in Category 1 LAMAs account for 78 % of total domestic emissions. Using the model output at the monitoring site, Figure 9 shows that a 35 % reduction in this portion of domestic heating



emissions results in a Robust Highest Concentration (RHC)<sup>#</sup> of  $47 \mu\text{g m}^{-3}$ . The same reduction of concentrations is also achieved for the maximum concentrations, since it is close to the RHC (not shown).



**Figure 9 Response of the modelled RHC of the moving 24-hour  $\text{PM}_{10}$  at the monitoring site to reductions in domestic emissions in category 1 LAMAs. This is based on TAPM results without wind data assimilation.**

The predictive model provides a link between concentrations and emissions, and shows a close to linear relationship between them. Hence, according to the model, emissions should be decreased at least linearly in the interim to reduce the highest concentration below  $50 \mu\text{g m}^{-3}$  by 2013.

### Example 3: Christchurch

TAPM is also used for investigating reduction strategies for  $\text{PM}_{10}$  emissions in Christchurch. The test case year chosen is 2002, as the latest emissions inventory was carried out by Environment Canterbury for this year. In this section a regression of the number of days Christchurch experiences poor air quality on emissions of  $\text{PM}_{10}$  into the atmosphere is carried out. The relationship is between  $\text{PM}_{10}$  exceedences and emissions is obviously dependent on the local meteorology, therefore the its effect may be removed by repeating the model experiment with the same meteorology (that of June, July and August 2002), but varying emissions according to chosen scenarios.

The methodology is as follows:

- 1) use the 2002 Christchurch inventory for  $\text{PM}_{10}$  in an 'area source' configuration;
- 2) run TAPM for June, July, and August using the 2002 inventory;
- 3) reduce emission levels by 15% successively and re-run the model to calculate new sets of pollution concentrations under the same meteorological conditions.

The Christchurch inventory distributes emissions spatially in a simplified way, considering the inner-city suburbs as one homogeneous region, and the surrounding suburbs as another. In reality, the source distribution is far more complex. Christchurch's poor air quality is mostly due to heterogeneously spaced point sources (houses) emitting smoke into a stable atmosphere at night. With current airshed modelling techniques and computational speed, it is not possible to simultaneously simulate each dwelling as a separate point source. Hence the sources

<sup>#</sup> It is arguably better to compare modelled RHC with observations (Willmott, 1982). The maximum may be an outlier, whereas the RHC is smoothed over the highest concentrations. The RHC is given by

$$\text{RHC} = C_{\text{mean}10} \cdot \ln(16) + C_{11} \cdot (1 - \ln(16)),$$

where  $C_{11}$  is the 11<sup>th</sup> highest concentration and  $C_{\text{mean}10}$  is the average of the highest ten concentrations. The RHC may be slightly larger than the maximum if there are no outliers.

are projected onto a regular grid in TAPM, which allows for spatial heterogeneity in emissions over an extended area. For the model experiments here, a simplified area-source configuration is used.

The preliminary emissions reduction scenario is shown in Figure 10. Emissions are reduced by the same fraction for every hour of the day. This might not represent the most realistic or efficient way to reduce daily averaged concentrations of PM<sub>10</sub>, yet it is a good starting point. In future model experiments, total emissions will be reduced by 15%, but entirely during the evening hours.

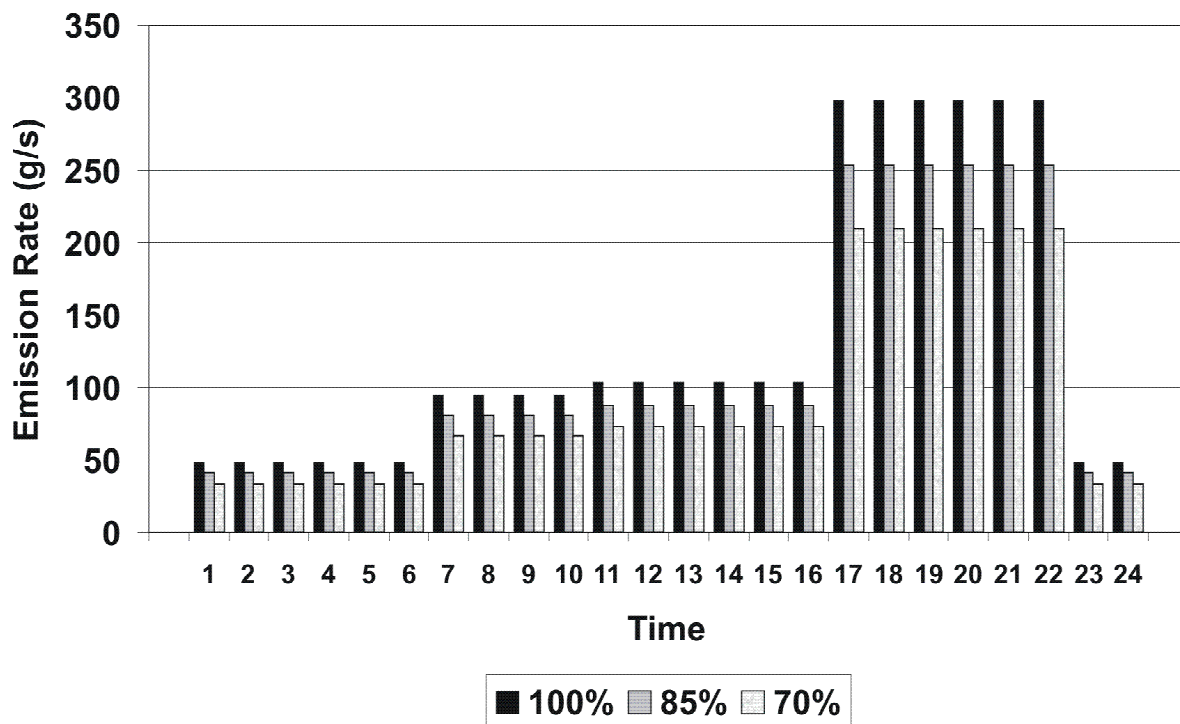


Figure 10 Hourly emission rates under the chosen emissions reduction scenarios.

Figure 11(a) illustrates the statistics derived from TAPM experiments for the high end of the PM<sub>10</sub> concentration distribution. The first dataset is derived from the grid point corresponding to the St. Albans (Coles Place) monitoring site commissioned and operated by Environment Canterbury (Figure 11(a)), whereas statistics shown in Figure 11(b) are taken from the model grid point with maximum PM<sub>10</sub> concentration. There is a linear response by all statistical indicators to the reduction in emission rate. Figure 11(a) shows that the model under-estimates the concentrations at St. Albans, which is to be expected as the emissions are assumed to be homogenous across the domain.

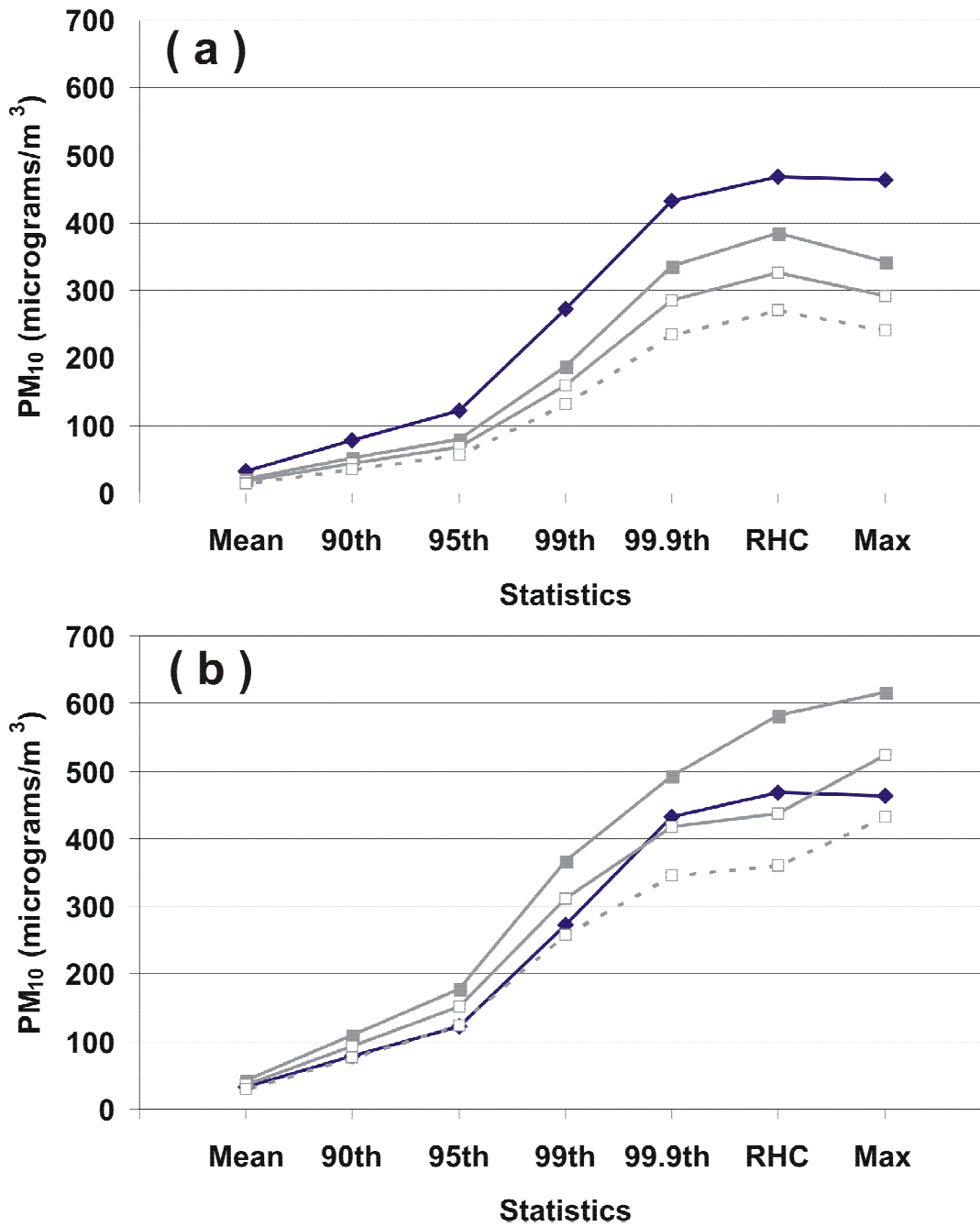
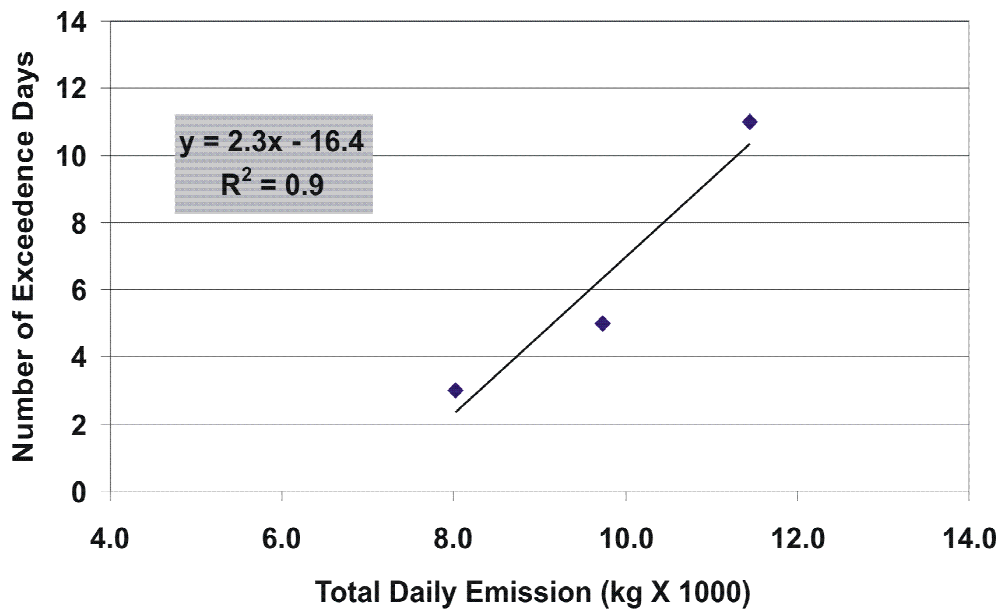


Figure 11 Statistics for emission scenarios. Filled-grey squares represent emissions at present-day levels, white-squares at 85%, and the dashed line at 70%. The blue diamonds represent observed data. The model statistics are derived from (a) the grid point nearest to St. Albans, and (b) the grid point of maximum  $PM_{10}$ .



**Figure 12 Relationship between total daily emission of PM<sub>10</sub> and number of exceedences.**

Figure 12 shows the relationship between total daily emissions and modelled number of exceedence days – defined as daily-averaged concentration greater than 50 µg m<sup>-3</sup>. The modelled value is extracted from the grid point of maximum concentration. With the present-day emission levels, the number of high pollution days is 11. This compares well with observations at St Albans, where there are 12 exceedences. The regression equation indicates that for every tonne of reduction in PM<sub>10</sub> emissions per day, the number of exceedences during the winter will decrease by 2 over the Christchurch urban area.

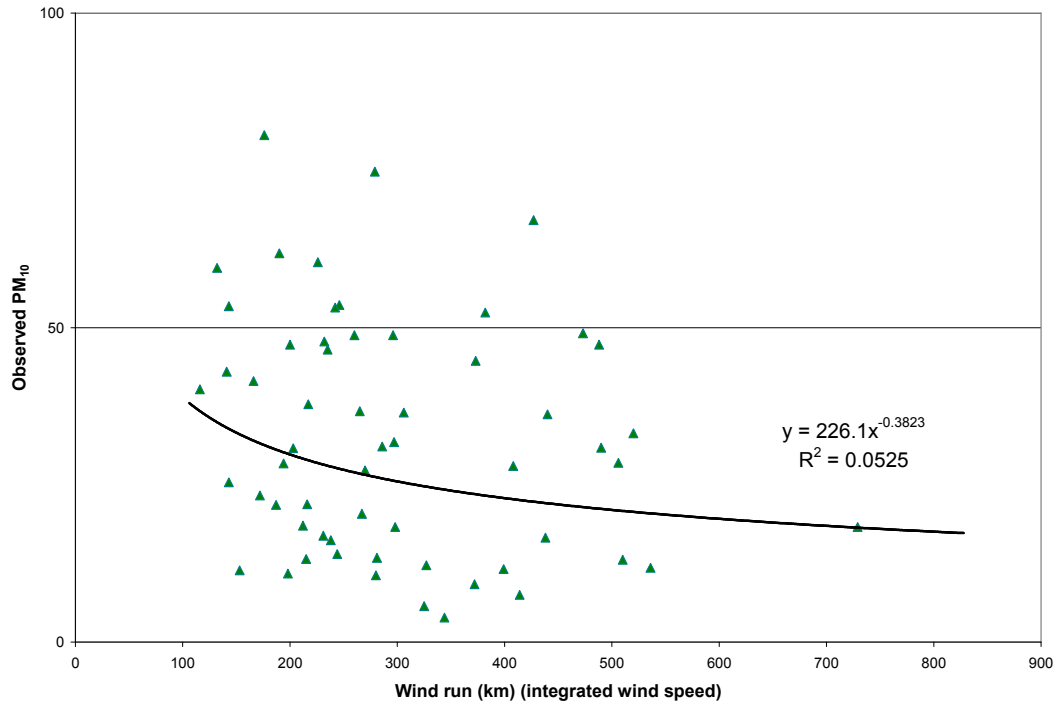
The results of these preliminary experiments should be interpreted with caution. So far, there appears to be a linear relationship between the number of days Christchurch experiences poor air quality and the emission of PM<sub>10</sub>. This can provide an emission reduction amount that may be used by local government as an annual ‘target’.

### Example 4: Blenheim

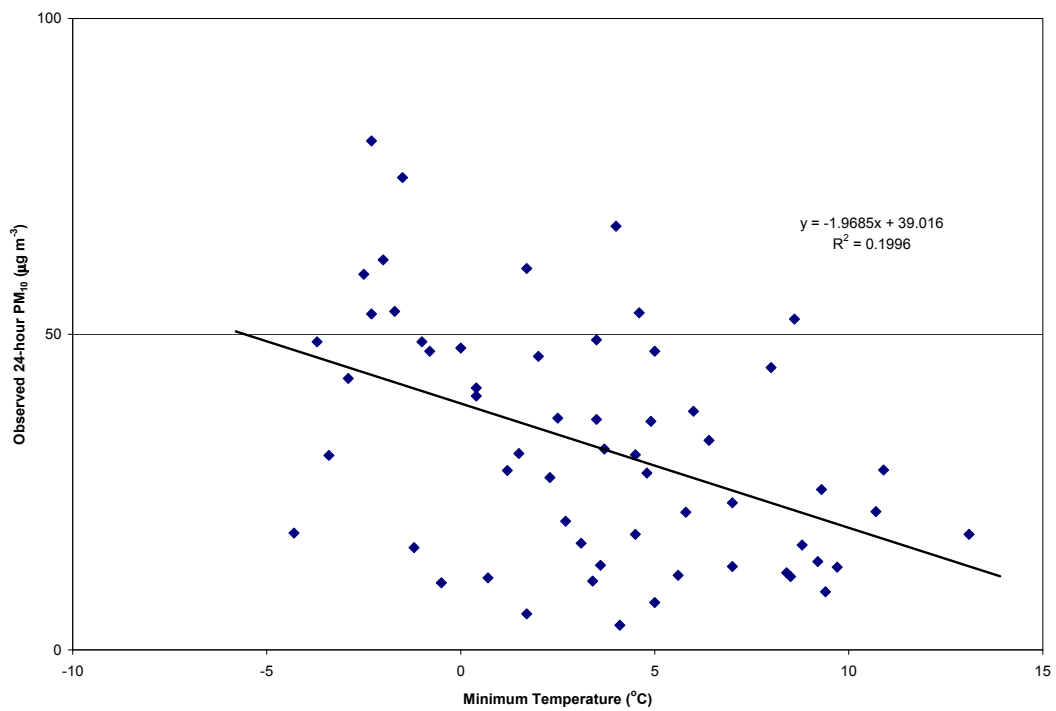
Blenheim is located on the flat river plain of the Wairau valley, and has a population of around 22,000. As is the case with many urban areas in New Zealand, it suffers poor air quality at times in winter and exceeds the NES for PM<sub>10</sub>. And, like other areas, this is primarily due to emissions from domestic heating.

Blenheim has two ambient air quality monitoring sites - at Middle Renwick Road and Redwoodtown and hourly winds and temperatures have been obtained from the Blenheim airport AWS (Automatic Weather Station). PM<sub>10</sub> concentrations in 2004 were measured once every 3 days at the Redwoodtown road site and every 5 days at Middle Renwick Road. There were 10 PM<sub>10</sub> exceedences at the Redwoodtown site during winter 2004.

Before carrying out modelling studies – this applies to any region – it is informative to examine the observations to ascertain relationships among the data. It is particularly useful to examine connections between air quality and meteorological parameters, as the airshed model simulates these in detail, to add to our understanding of the air quality processes. At other sites examined in this report there is a clear inverse relation between the observed PM<sub>10</sub> concentrations and the observed mean daily wind speed. For Napier, this relationship explains around three-quarters of the variance in PM<sub>10</sub> (see above). However, the same calculation for the Blenheim sites shows far more scatter (Figure 13(a)), with wind speed explaining no more than 10% of the variability in PM<sub>10</sub>. Slightly more of the variation in PM<sub>10</sub> (up to 20%) is explained by relating it to the observed daily minimum temperature (Figure 13(b)). This may be due to increased atmospheric stability in colder conditions limiting dispersion, or changes in emission rates through increased domestic heating as a response to colder temperatures.



(a)



(b)

Figure 13 Relationships between  $PM_{10}$  and meteorological data in Blenheim for Winter 2004. (a) Redwoodtown  $PM_{10}$  versus wind run (daily-integrated wind speed), with best-fit inverse power-law trend fitted; (b) Redwoodtown  $PM_{10}$  versus night-time minimum temperature, with best-fit linear trend.

These findings present a challenge for airshed modelling. Traditionally, the model determines the meteorology hour by hour, but uses the same emissions each day. Emissions data come from an inventory, based on a 'typical' or 'worse case' day, and variability of emissions is not accounted for. If this same approach is followed for the Blenheim case, model performance is not as good as those cases where the PM<sub>10</sub> levels are controlled largely by the meteorology. TAPM is configured in a similar manner to the Masterton and Hawke's Bay examples, with meteorology in the Wairau valley simulated at 1 km resolution and dispersion at 500 m. Emissions data from Fisher *et al.* (2005) are used. Runs are carried out for the month of July 2004. Model estimates of PM<sub>10</sub> levels were extracted hourly at the nearest grid points to the two air quality monitoring sites at Redwoodtown and Middle Renwick Road. Figure 14 shows the observed and modelled 24-hr PM<sub>10</sub> concentrations for July 2004 at these sites. The maximum model PM<sub>10</sub> value within a 1.0km radius and the maximum over the whole grid are also shown. There is a general underestimation of PM<sub>10</sub> levels by the model, but also the day to day observed trends are not matched by the model either. This requires further investigation – firstly to ensure that the meteorology is simulated well by the model, and secondly to investigate the emissions and their variability more closely. (An inventory has been compiled specifically for the region, but those data have not been used here).

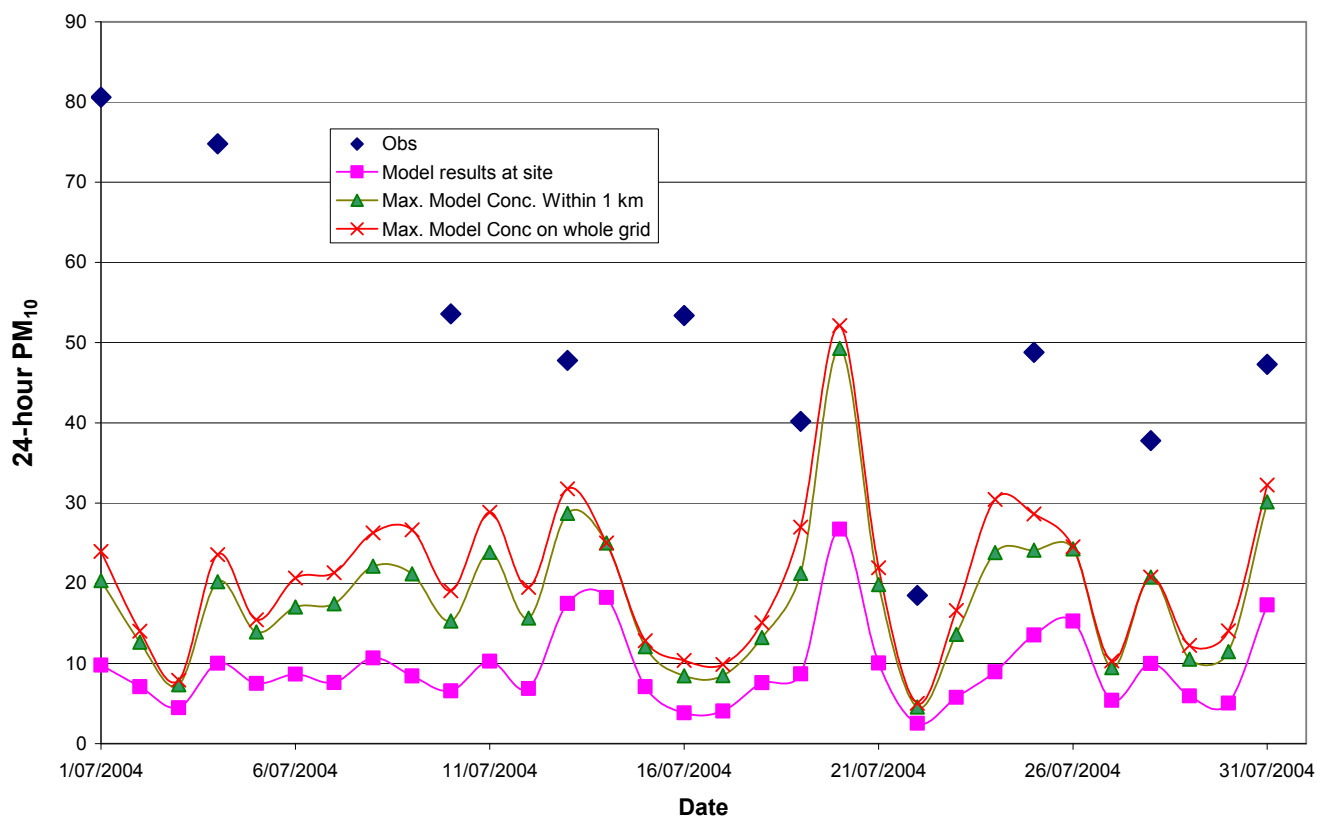


Figure 14 (a) Modelled and Observed PM<sub>10</sub> concentrations at Redwoodtown.

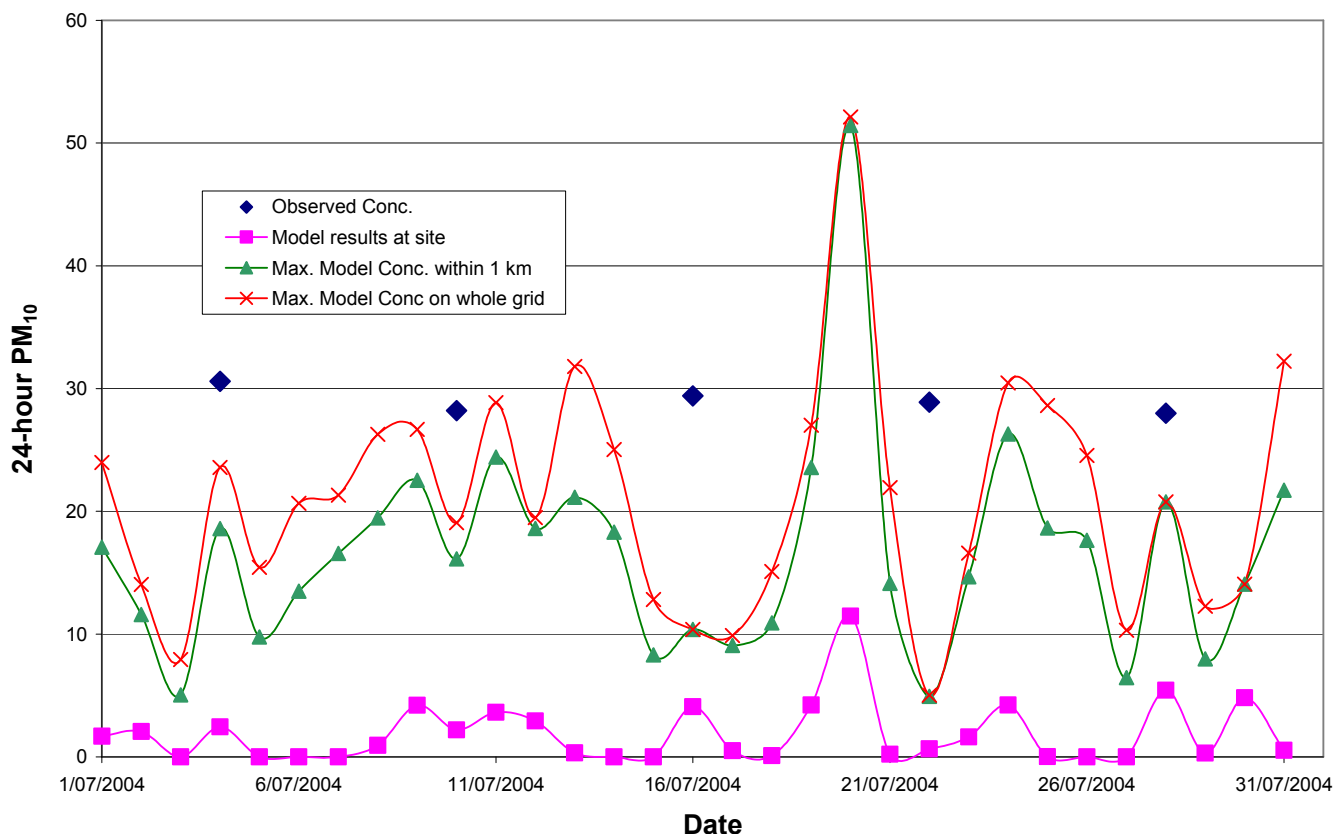


Figure 14 (b) Modelled and Observed PM<sub>10</sub> concentrations at Middle Renwick Road.

Figure 14 Modelled and Observed PM<sub>10</sub> concentrations (a) Redwoodtown (b) Middle Renwick Road.

## Discussion

This report describes methodologies for applying urban airshed models to the implementation of the NES, with reference to specific cases. The models have been used to simulate present-day air quality and make predictions of emissions reductions required to achieve the PM<sub>10</sub> Standard. Having worked through several cases, rather than simply presenting hypothetical ideas, some important issues have presented themselves. They arise in air quality science and dispersion modelling in general, but are described here with particular reference to NES, SiPs, LAMAs, emissions inventories and air quality observational networks.

## Model Validation

This is an important stage in the modelling process – the model must be shown to produce good results for present-day conditions before being extrapolated to new situations. The new situation may simply be current air quality in location where there is no monitoring, or a prediction of future PM<sub>10</sub> levels under some prescribed emissions reduction scenario.

It is important to assess model performance for all processes leading to the modelled PM<sub>10</sub> concentration – emissions, meteorology, dispersion, observation. This is known as *process analysis*. If there are errors, their source must be found. For instance, a good meteorological simulation, but a bad simulation of pollution concentration points to problems with the inventory or the dispersion model. Conversely, if the processes are not checked individually, then the output PM<sub>10</sub> may match observed PM<sub>10</sub> well, but only through cancellation of errors along the way.

Statistical measures have been used here which assess model performance over the broad range of simulated conditions (means, correlations, indices of agreement), and under conditions of high PM<sub>10</sub> concentration (maximum value, robust highest concentration, 99.9<sup>th</sup> percentile). Of interest here is the occurrence of NES breaches, which are under extreme conditions (calm, stable atmosphere, high emissions, high PM<sub>10</sub> levels). These are – each in a different way - the most difficult for the model to simulate. This feature is addressed in more detail below.

The model is validated by comparison with meteorological observations and air quality monitoring. These must be detailed enough so that a good comparison may be made. Meteorological sites are generally sparsely spread through New Zealand. Air quality monitoring may comprise a 24-hour-average PM<sub>10</sub> concentration at one location in an urban area every three or six days. If the model concentration does not match the observed PM<sub>10</sub>, it is almost impossible to determine why. One key uncertainty is the contribution to observed PM<sub>10</sub> from motor vehicles. According to the model, it may be negligible, but the true contribution will depend on the distance of the monitoring site from the highway. Ideally, hourly PM<sub>10</sub> data should be available from the same location as hourly climate variables (winds, temperature, humidity). This may reveal peaks in PM<sub>10</sub> at peak-traffic times. This situation is improving, as all Regional Councils are now carrying out continual monitoring at their air quality sites.

## Modelling Worst-Case Conditions

Variability in meteorology from year to year leads to variability in pollution concentrations. Some years have worse air quality than others. Under NES only one PM<sub>10</sub> exceedence is permitted in *any* year – model predictions thus need to be made for the *worst-case* year to ensure that predictions (of concentrations, or necessary emissions reductions) are conservative. This could be achieved by modelling the last, say, ten years, but at present this can be computationally prohibitive<sup>#</sup>. A methodology is needed whereby an appropriate year is chosen for modelling, with some certainty that the results will be conservative. An example method follows:

- (i) Examine PM<sub>10</sub> and meteorological data during years for which PM<sub>10</sub> data are available, searching for – and establishing – relationships between pollution levels and meteorological conditions, *viz.*
  - a. PM<sub>10</sub> levels,
  - b. Number of PM<sub>10</sub> exceedences,
  - c. Local wind speed,
  - d. Local temperature,
  - e. Frequency of calms,
  - f. Frequency of temperatures below some threshold.

These parameters apply on a 24-hourly basis, and, usually, there should be a good correlation between measures of PM<sub>10</sub> and wind.

- (ii) Examine local meteorological data for the last, say, ten years to find the year with the worst-case air-pollution meteorology.
- (iii) Model that year with present-day emissions to determine worst-case PM<sub>10</sub> levels, and follow the techniques described here to determine emissions reductions required to follow the SLiP or CLiP.

Note that this methodology will only work if a relationship between the state of air quality and the meteorology can be found in (i). It should usually be found that PM<sub>10</sub> levels are related to the frequency of calms, or local wind speed. For the Hawke's Bay case, the correlation between daily PM<sub>10</sub> at Nelson Park and frequency of calms (the number hours per day the wind speed is less than or equal to 1 m s<sup>-1</sup>) at Napier Airport AWS is 0.77.

Note also that there may be a mismatch between the emissions inventory year and the chosen year of meteorology, or there may no PM<sub>10</sub> data for that chosen year (because it is too far in the past). Hence the configuration chosen in (iii) is in a sense hypothetical and cannot be directly validated. Therefore model should still be validated, choosing a recent period for which PM<sub>10</sub> data are available, and the inventory data are appropriate.

Results presented in this report show that care must be taken with predictions of the number of PM<sub>10</sub> exceedences under the worst-case meteorological conditions. If the validation procedure shows that those

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<sup>#</sup> Even so, USEPA modelling guidelines recommend models be run for five years.



extremes are not simulated well by the model (that is, some exceedences are missed), then this is likely to still occur in the (hypothetical) worst-case year.

## Emissions Inventories

A detailed inventory requires considerable resources to construct and is subject to uncertainty. The recent PM<sub>10</sub> inventories for NZ, using the CAU (typically around 3,000 to 5,000 people in urban areas) as the basic working unit, provide a reliable spatial presentation of emissions, but the methodology still requires refinement. It is recommended that for policy development, inventories specific to the region in question should be developed and used in preference to the more generic estimates in the national inventory. The region-specific inventories are being compiled using more realistic methodologies (see Wilton (2001)). These will, in time, be incorporated into the National Pollution Inventory.

New requirements for emissions inventories have arisen as a result of the NES (see King *et al.* (2005)). Specifically, daily emissions estimates need to be partitioned into smaller time periods. Most region-specific inventories break the day into several-hour periods. The inventory for Auckland uses hourly profiles. Estimates of hourly emissions profiles have been used in the current modelling. Also, seasonal trends in emissions are needed, as not all exceedences occur in winter.

The model runs described here use a 'typical' spatial and temporal emission pattern and assume the pattern is the same each day. Hence the model only simulates the effects of day-to-day differences in the meteorological situation in producing variations in PM<sub>10</sub> concentration. The model simulates the variation in PM<sub>10</sub> levels due to meteorological variability, but not due to variability in emissions. It may be that exceedences of PM<sub>10</sub> may be caused by extreme emissions, which will therefore not be simulated by the dispersion models as they are currently configured. For instance, emissions may be elevated by extreme cold, high motor vehicle traffic or a fire. Ways must be developed which account for variation in emissions, so that models better reproduce the high levels of PM<sub>10</sub> which can be observed.

## Meteorological Modelling

The performance of the meteorological part of the models has been assessed through comparison with data from climate sites, using standard statistical measures of model skill. However, these measures consider the model performance 'on average', whereas the detailed aspects of the meteorology can determine whether pollution events occur. TAPM reproduces the general conditions well, but not always the extremes of calm winds and cold, stable nights (and this means that a comparison between modelled and observed wind roses should focus on the low winds in the inner part of the rose). These extremes are the occasions on which high PM<sub>10</sub> concentrations arise. Cases where a PM<sub>10</sub> exceedence has been missed by the model are being examined more closely, on an hour-by-hour basis.

One useful feature of TAPM is that it allows the assimilation of wind observations. If data are present, the modelled wind is 'nudged' towards the observations in the area near the monitoring site. However, this can have mixed effect on pollution dispersion results, and the approach should be used with caution. TAPM is designed specifically to produce good results (in a statistical sense, rather than from day to day) without the need for local meteorological data because there may be none available (Hurley *et al.*, 2003) – any available data are used in the model validation process.

There remains then the difficulty of the simulation of calm, stable conditions, which *could* be improved by wind data assimilation. To accomplish this without data assimilation, model simulation of the night-time inversion layer may be improved by changing some of the model's surface characteristics. These include the terrain height, soil type, deep-soil temperature and moisture content, sea-surface temperature, and land-use category. Altering the land-use category will change such parameters as the roughness length, leaf area index and surface heat and moisture capacity. A detailed investigation of these has yet to be carried out.

It is also important to obtain a good simulation of the near-surface temperature, and data assimilation is not available in TAPM for this parameter. Its effects on pollution dispersion are two-fold. Firstly, the vertical temperature gradient determines atmospheric stability and dispersion characteristics. Errors in modelled screen-level temperature may be symptomatic of an inversion which is too weak, and conditions would be too dispersive.

Secondly, domestic heating emissions may increase when it is colder. It is a challenge in TAPM to improve the first of these effects, and this has to be done through changes in the model's surface characteristics. TAPM may also be run in a temperature-dependent emission mode, which may remove some of the uncertainty associated with varying emissions.

## Local Air-quality Management Areas

LAMAs are defined essentially by patterns of  $PM_{10}$  emissions, and mitigation measures will be based on emissions reduction policy, yet the Standard for  $PM_{10}$  is based on extreme concentrations. The link between concentrations and emissions has been provided through predictive modelling. There is still debate over whether LAMAs should be defined in terms of emissions or concentrations. In the current work regions of  $PM_{10}$  concentration above  $50 \mu\text{g m}^{-3}$  have been seen in model results *outside* the category 1 LAMA, but due to emissions *from within* the category 1 LAMA. This leads to a slight redefinition of a category 1 LAMA, from a region whose emissions can lead to  $PM_{10}$  exceedences, to a region whose emissions can lead to  $PM_{10}$  exceedences, possibly several kilometres away.

The modelling may be used to re-assess the LAMA classification given to CAUs. For example, an urban area designated as category 1 due to its observed  $PM_{10}$  exceedences may be surrounded by LAMAs so-far designated as category 2 because there are no  $PM_{10}$  observations and their emissions are lower. Including the surrounding areas in the same model domain, and subjecting them to similar meteorological conditions may result in modelled  $PM_{10}$  exceedences from these areas, indicating that they should also be category 1 LAMAs.

## Conclusion

This work has focussed on modelling winter pollution events, with the  $PM_{10}$  emitted from domestic fires as a primary pollutant. This suits the configuration of TAPM, in which the sources may be assumed areally spread, and representable on a model grid. However, the concepts and methodologies need to be extended, to address

- (a) regions where other sources dominate, which must be represented as line sources (motor vehicles) or elevated point sources (industrial stacks). There is still considerable uncertainty over sources of  $PM_{10}$  from re-suspended road-dust. Other kinds of model may be more suitable in these cases;
- (b) chemical transformations of gaseous pollutants and the production of secondary particulate matter. TAPM includes a simple chemical mechanism which may be suitable for this, but emissions of precursor pollutants (such as  $NO_x$ ,  $SO_2$ , VOCs,  $NH_3$ ) need to be included in the inventory;
- (c) summer  $PM_{10}$  episodes. During summer, there will be no domestic fires in use, and motor vehicles will become a dominant source of  $PM_{10}$  in all regions;
- (d) 'natural' emissions of  $PM_{10}$ , such as sea spray or fugitive dusts.

Work on these is in progress through all the programme objectives.

## Acknowledgements

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