Modelling wintertime PM_{10} dispersion in Masterton, New Zealand: a tool for implementing national standards

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Abstract

The National Environmental Standards (NES) for air quality have recently been introduced in New Zealand (NZ). Many urban areas experience high levels of PM_{10} and compliance with the regulations for concentrations of PM_{10} and other pollutants must be achieved by 2013. This study uses urban airshed modelling techniques as a tool for assessing effects of pollution mitigation options. Masterton is a rural town with regular exceedences of the PM_{10} standard over winter, due largely to emissions from wood burning for home heating. A simulation of PM_{10} dispersion in Masterton for the winter months of 2003 has been carried out using TAPM (Version 3) on nested horizontal grids, down to 1 km spacing for meteorology and 0.5 km for pollution. Statistical measures of model performance show that the model performs well for both meteorology and pollution. The model links concentrations and emissions, showing an approximately linear relationship between them, although the number of exceedences is expected to decrease an approximate 15% reduction of domestic emissions has been achieved. The results demonstrate that modelling can be a useful tool for assessing emission reduction scenarios for NES compliance. Urban airshed modelling is a challenging task in coastal regions or complex terrain (typical of most NZ cities), particularly for regulatory purposes due to the requirement of simulation for extended periods at high temporal and spatial resolution. In addition, for small towns like Masterton, airshed modelling is a new technique. Therefore, this study represents a significant step forward for the application of airshed modelling in NZ and elsewhere.
Keywords: TAPM, home heating emissions, air pollution, dispersion modelling, Masterton, New Zealand, National Environmental Standards.

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1 Introduction

The National Environmental Standards (NES) for ambient air quality came into effect in New Zealand (NZ) in September 2005. The Standard for PM_{10} (particles with diameter less than 10 μm) requires that the 24 hour average concentration of 50 μg m^{-3} is not to be exceeded more than once per year. There are many urban areas currently not complying with the NES. Compliance for PM_{10} must be achieved by the year 2013 [1].

Pollution mitigation options designed to attain NES depend on reduction of emissions and the use of models to predict the effects of such measures on concentration levels in the future. Validated models are acknowledged to be an element of an effective air quality management framework 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.

In this work, a prognostic modelling approach solving the fundamental fluid dynamics and scalar transport equations to predict meteorology and pollutant concentrations is taken. Urban airshed modelling for regulatory purposes is a challenging task, due to the requirement of simulation for extended periods at high temporal and spatial resolution, under complex meteorological and dispersion conditions (e.g., in coastal regions or complex terrain) [2]. These are typical of most NZ cities. In addition, adequate emissions data are not always available. In NZ, airshed modelling has been applied to the major cities, of Auckland and Christchurch [3]. For smaller towns like Masterton, airshed modelling is a new technique and this study represents a significant step forward for the application of airshed modelling in NZ and elsewhere.

Masterton district, with an urban population of about 18000, is situated in the Wairarapa area in the south east of the North Island. The urban centre is located on the flat river plain of the Wairarapa Valley which is approximately 20 km wide, with the steep slopes of Tararua Ranges to the west. Regular PM_{10} exceedences occur in winter due to emissions of particulates from domestic heating [4]. Airshed modelling has not previously been carried out for this region. In this study, we use The Air Pollution Model (TAPM; Hurley *et al.* [5]) to simulate PM_{10} dispersion in Masterton during the winter of 2003. TAPM is able to assimilate the observed wind, thereby improving the meteorological model results and providing better fields for dispersion modelling. Data from a recent national inventory [6] are processed to provide model inputs (see section 2), and model results are compared to air quality monitoring data. Estimates of emission reductions required for NES compliance are assessed using the model. This study is part of an on-going research programme to protect New Zealand's clean air [7].

2 Model configuration

TAPM is a nestable, prognostic meteorological and air pollution model. It is based on the fundamental equations of atmospheric flow, thermodynamics, moisture conservation, turbulence and dispersion. It runs efficiently on a PC and

includes a user-friendly interface. The model has been extensively evaluated for a wide range of observed meteorological and air pollution situations [8]. TAPM (version 3) was run for winter months May to August, 2003. Four grids (numbered 1 to 4, in order of increasing horizontal resolution) were used, centred on the Masterton urban area. Each meteorological grid contained 25×25 points in the horizontal, with resolutions of 30, 10, 3 and 1 km. The two innermost grid domains are shown in Figure 1. The corresponding dispersion model grids covered the same areas but at twice the resolution, each containing 49×49 points, with the finest grid at 0.5 km resolution. 25 vertical levels were used, with the lowest 10 m and the highest 8000 m above the ground. A deep soil moisture content of 0.25 kg kg^{-1} was used for May, and 0.3 kg kg^{-1} for June to August. The model simulated rain and snow processes. Default values of the other parameters were used.

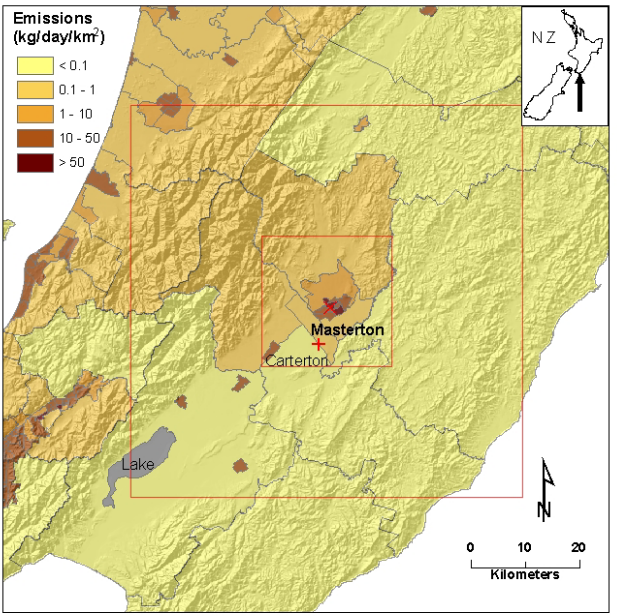

Figure 1: TAPM model domain with nested Grids 3 and 4 outlined. CAUs are shaded according to the magnitudes of their domestic PM_{10} emissions. The ambient monitoring site at Wairarapa College (×) and the East Taratahi meteorological site (+) are also shown.

A national PM_{10} emissions inventory has recently been developed and used in the definition of NZ local air management areas [6]. The Geographical Information System (GIS) based inventory includes industry emissions (point sources), domestic and vehicle emissions (presented as averages for 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, brake wear, tyre wear and road dust re-suspension. In Masterton, domestic, vehicle and industry sources account for 80%, 17% and 3% of PM_{10} emissions respectively. CAU boundaries are shown in Figure 1 and CAUs are shaded according to emissions from domestic fires. There are three CAUs (Ngaumutaw, Masterton West and Masterton East) in Masterton urban areas with high domestic emissions (>50 kg/day/km^2). The inventory data were processed for input to TAPM, representing wood burner and vehicle emissions as area sources (on the 500 m grid, with diurnal variation) and industrial emissions as point sources (constant in time). PM_{10} is treated as a conserved tracer.

The Masterton ambient air quality monitoring site at Wairarapa College and the East Taratahi meteorological site are located in the finest grid. Hourly PM_{10} concentrations, wind speed, wind direction and temperature were measured at the air-quality site [4]. PM_{10} is measured by using the tapered element oscillating microbalance (TEOM) method. In this study, the TEOM data are not corrected for the loss of semi-volatile components of the particulate due to lack of an appropriate adjustment factor for the area. Hourly wind speed, wind direction and temperature data at East Taratahi were obtained from the National Climate Database (CLIDB). The wind speed and direction data from the Masterton and the East Taratahi sites were assimilated into the lowest model level (10 m) with specified radii of influence 2 and 4 km, respectively.

3 Results

3.1 Validation of the meteorological model

Model predictions of meteorology were extracted at the nearest grid points to the Masterton and East Taratahi sites on the 1 km grid. Model results are examined to assess the ability of the model to simulate extreme conditions and the general agreement between modelled and observed conditions over the whole simulation period. The statistical performance measures used here are those frequently applied for model evaluations [2], including the correlation (Cor) between observed (O) and modelled (M) values, arithmetic mean (A), standard deviation (S), root-mean-square error (RMSE), index of agreement (IOA), S_V (= S_M / S_O, showing skill if close to 1), and S_R (= RMSE / S_O, showing skill when less than 1). The IOA can vary between 0 (no agreement) and 1 (complete agreement) with values above 0.60 considered a good agreement between modelled and observed parameters.

The performance statistics, when compared with hourly wind speed and temperature observations at the Masterton (MT) and the East Taratahi (ET) sites, are shown in Table 1. Simulated wind speed agrees well with observations for both sites, with IOA values of 0.91. Since wind speed cannot go below zero, the statistics can look good even if directions are wrong. Therefore, we need to analyse the west-east (u) and south-north (v) components of wind speed. For both components, Table 1 also shows a good agreement between modelling with observations. However, at Masterton, the over-prediction of the northerly

component of wind speed results in a negative mean value (A_M) for v component, compared to a positive mean value (A_O) from observations. Although temperature data are not assimilated in the model, results for temperature are satisfactory for both sites with IOA values greater than 0.85. However, modelled temperatures show less diurnal variations than the observations, resulting in small S_V values and smaller S_M values than S_O values.

Table 1: Statistics for the simulation at Masterton (MT) and East Taratahi (ET).

Site	A_O	A_M	S_O	S_M	Cor	RMSE	IOA	S_V	S_R
Wind speed (m s^{-1})									
MT	1.9	2.2	1.4	1.6	0.86	0.89	0.91	1.12	0.61
ET	2.8	3.0	2.3	1.9	0.84	1.26	0.91	0.85	0.55
Westerly wind component (u) (m s^{-1})									
MT	0.3	0.6	1.6	1.6	0.79	1.10	0.88	1.00	0.67
ET	0.6	0.7	2.8	2.5	0.86	1.44	0.92	0.90	0.52
Southerly wind component (v) (m s^{-1})									
MT	0.1	-0.5	1.7	2.1	0.85	1.24	0.89	1.21	0.73
ET	-0.5	-0.8	2.4	2.4	0.91	1.06	0.94	0.99	0.45
Temperature (^{o}C)									
MT	9.4	9.4	4.4	3.1	0.86	2.32	0.90	0.71	0.53
ET	8.6	8.7	5.1	3.7	0.87	2.66	0.90	0.72	0.52

Wind roses constructed from the observed and modelled data at Masterton and East Taratahi (not shown) are compared. Model outputs simulate the south-westerly and north-easterly winds, the two most common flow directions, reasonably well. These are determined to a large extent by the orientation of the valley and surrounding hills. There are more northerly winds from the model than from the observation. Model results for calm conditions (<1 m s^{-1}) are also reasonably good; these and the component between 1 and 3 m s^{-1} are the conditions important for air-pollution events. Observations of calm periods are 32.2% and 17.3% at Masterton and East Taratahi respectively, compared to modelled 24.2% at Masterton and 11.9% at East Taratahi.

3.2 Validation of the dispersion model

Model predictions of ground-level PM_{10} were extracted at the nearest grid point to the Masterton site on the 0.5-km grid. Model results are examined to assess the ability of the model to simulate peak concentrations and the general agreement between modelled and observed concentrations over the whole simulation period. The statistical performance measures used here are similar to those used for the meteorological modelling in Section 3.1, in particular those relating to the highest values obtained. The IOA can vary between 0 (no agreement) and 1 (complete agreement) with values above 0.60 considered a good agreement between modelled and observed parameters. Of particular interest is the robust highest concentration (RHC). This is a preferred statistic for

the model's simulation of the high end of the concentration distribution. RHC = C(R) + (Cp - C(R)) × ln ((3R-1)/2), where C(R) is the Rth highest concentration, and Cp the mean of the top R-1 concentrations. A value of 11 for R is used [2].

Concentrations of sea spray and windblown dust are difficult to quantify and appropriate emissions estimates are not available in the inventories. Their contributions are usually accounted for as a constant "background" [2]. Improving the estimate of this background concentration is a topic of on-going research in air quality. Since PM_{10} is treated as a conserved tracer in our model runs, secondary particulate contributions are included in the background concentration. In this study, the correlation between PM_{10} and carbon monoxide (CO) is used to estimate the background concentration.

Based on the knowledge that combustion processes release PM_{10} as well as gaseous pollutants, e.g., nitrogen oxides (NOx) and CO, while there are no gaseous pollutants from non-combustion processes. Investigating the association between PM_{10} and these gases (as combustion PM_{10} tracers) can quantify contributions of combustion and non-combustion sources. Linear regressions can be used to derive the relationship. The approach has been applied for estimating PM_{10} sources from vehicle and non-vehicle emissions in UK cities [9]. Later, it was pointed out that NOx and CO emissions from non-traffic sources should be considered [10].

In Masterton, combustion sources include domestic and vehicle emissions. CO is considered a suitable tracer. Since the ratio of PM_{10} and CO is different between the two source-types, 24-hour average data are used to smooth out hourly variations of PM_{10} and CO ratios. The linear regression of PM_{10} and CO concentrations apportions PM_{10} into combustion (associated with CO) and non-combustion (or background, independent of CO) components. In order to account for random measurement errors in PM_{10} and CO concentrations, the reduced major axis regression is used rather than the standard linear regression [11]. The regression result is PM_{10} ($\mu g\ m^{-3}$) = 37.476 × CO (ppm) + 8.0, with R^2 = 0.90. The intercept represents the average PM_{10} concentration when there are no combustion contributions, i.e., zero CO concentration. This results in an average background PM_{10} concentration of 8.0 ± 1.0 $\mu g\ m^{-3}$ (the uncertainty is the 95% confidence interval), which accounts for contributions from sea salt, windblown dust and secondary particulate for the modelling period.

The PM_{10} modelling results, reported as the sum of the TAPM output and the background concentration, are satisfactory with an average of 23.2 $\mu g\ m^{-3}$ from modelling, compared to 22.2 $\mu g\ m^{-3}$ from monitoring. Assessing model performance for paired-in-time PM_{10} (24-hour average) can be achieved through measures such as IOA and factor-of-two (the fraction of the time the modelled value is within a factor of two of the measurements). PM_{10} 24-hour concentrations are calculated as the averages of hourly data from midnight to midnight. The resultant IOA value is 0.68, with a factor-of-two of 0.81. These results indicate that the model performs well for paired-in-time prediction [2].

Figure 2 shows statistical measures of the high end of the 24-hour average concentration distribution. The model overestimates PM_{10} levels at the high end, above the 15th-ranked concentration. The simulated RHC is 87.4 $\mu g\ m^{-3}$,

compared to the observed value of 58.1 μg m^{-3}. The differences are consistent with the tendency for the TEOM to underestimate PM_{10} concentrations. Other possible factors such as overestimates in emissions or poor performance of the dispersion model are considered unlikely to be important since the model performs well for the seasonal-average and paired-in-time PM_{10} concentrations.

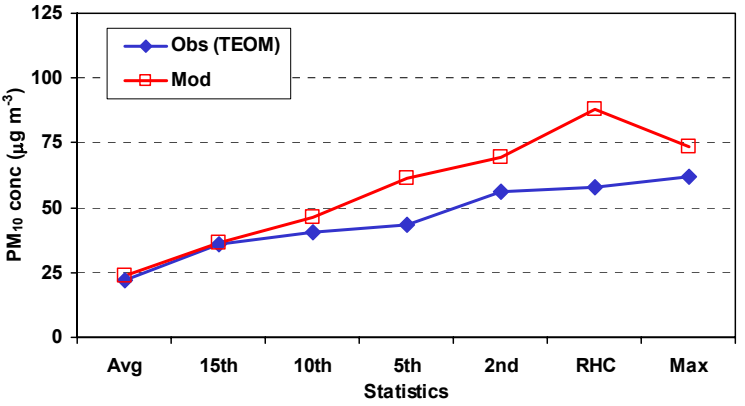

Figure 2: Statistics for observed (Obs, TEOM data) and modelled (Mod) PM_{10} concentrations at Masterton: average (Avg), 15^{th}, 10^{th}, 5^{th}, 2^{nd}, RHC and maximum (Max).

The spatial distribution of maximum 24-hour-averaged PM_{10} concentrations (not shown) demonstrates that areas of high concentrations coincide with areas of high domestic PM_{10} emissions and exceedence areas cover much of the Masterton urban region. The 'plume' is aligned with the dominant wind directions (NE-SW), but contours follow the terrain in the north-east and south-east – presumably due to draining wind from the hills in the north-west towards the town during calm nights. The spatial distribution of concentrations provides more detailed information about potential population exposure since maximum emissions and maximum concentrations can occur in somewhat different locations.

4 Examination of emissions reduction scenarios

Knowing source contributions to air pollution is essential to construct effective mitigation measures. The contributions from different sources in the inventory can be derived from the model output. During May-August 2003 at the monitoring site, the most significant source is home heating, contributing to around 53% (12.4 μg m^{-3}) of the total particulate concentrations, with vehicle and industry accounting for about 8% (1.9 μg m^{-3}) and 4% (0.9 μg m^{-3}), respectively. Other sources, including sea spray, windblown dust and secondary

particulate, contributing to approximately 34% (8.0 μg m^{-3}), as estimated from the regression of PM_{10} and CO daily concentrations (see Section 3.2).

A detailed projection of emissions into the future has not been completed. As a first scenario, Fisher *et al.* [12] suggested that reductions of 10%, 15% and 20% for industry, vehicle and domestic emissions, respectively, be used to estimate likely PM_{10} levels in 2013. Using these reductions and the 2003 meteorological input, modelling results show a maximum concentration of 60.3 μg m^{-3} with 5 exceedences occurring during the winter season. Therefore, this scenario of "business as usual" is not likely to attain the NES in 2013.

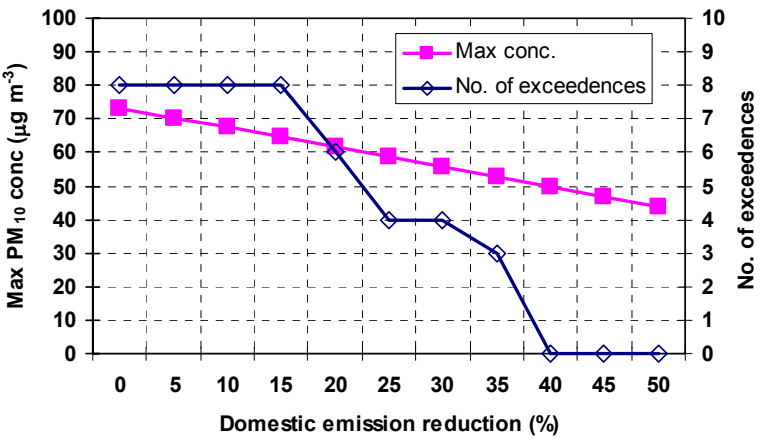

Figure 3: Response of the maximum 24-hour PM_{10} concentrations and the number of exceedences at the monitoring site to the reductions of domestic emissions. This is based on modelling results.

As half of all PM_{10} concentrations in urban Masterton are attributable to domestic heating, pollution mitigation options over the local region should focus on this source-type. Emissions from other source types are regulated differently - industry through resource consents, and vehicles through national measures. It is beyond the scope of this work to suggest what the mitigation options might be for domestic heating – however, the model can be used to assess the effects of progressive reductions. Using the model output at the monitoring site, Figure 3 shows that the maximum concentrations decrease linearly with reductions in domestic emissions. The projection of the number of exceedences may not be as reliable as the projection of concentrations. However, in order to provide information about the NES compliance of one allowable exceedence, a prediction of the number of exceedences is also shown in Figure 3. A 40% fall in emissions could achieve NES compliance at this site with the maximum concentration below 50 μg m^{-3} with no exceedence. In Masterton, PM_{10} levels are much higher in winter months (May-August) than in other months. Therefore, the maximum concentrations and the number of exceedences from

modelling are used for the whole year. More detailed emission reduction scenarios can also be analysed as better data becomes available from the local authority.

5 Discussion and conclusions

PM_{10} dispersion in Masterton has been successfully simulated using TAPM for the winter of 2003. Statistical measures of model performance show that the model performs well for both meteorology and pollution dispersion. The model links concentrations and emissions, and shows a close to linear relationship between them, and there is a significant drop in the expected number of exceedences after about 15% reductions of domestic emissions. Our results show that modelling is a useful tool for assessing emission reduction scenarios for NES compliance. They can also be used for studying human population exposure to particulate pollution.

A lack of high quality emission inventories is the main limitation to progress in particulate dispersion modelling in New Zealand [3]. A detailed inventory requires considerable resources to construct and is subject to uncertainty. The uncertainty is large for sources such as sea salt, re-suspended road dust and wind-blown dust. The recent PM_{10} inventories for NZ [6], 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. For Masterton, the inventory constructed in this way generates a satisfactory input for modelling and we expect that upgraded versions of inventories will contribute significantly to the success of airshed modelling in NZ.

Work is in progress to improve the modelling and further improve its usefulness as a planning and compliance tool for regulators. Source apportionment for ambient PM_{10} will be improved with detailed information about natural sources, i.e., sea salt and windblown dust, and the simulation of aerosol chemistry for secondary particulates. Further research is needed for a better understanding of the important meteorological processes related to elevated PM_{10} concentrations. This is one area in which modern prognostic models do rather well, but models still need substantial development to simulate dispersion in the calmest and coldest conditions. Airsheds have to be compliant with NES under the worst-case meteorological conditions.

Acknowledgements

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