Source Contributions to Ambient PM_{10} and Implications for Mitigation- a Case Study

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ABSTRACT

This report presents estimates of PM_{10} source contributions and analysis of mitigation effects by using airshed modelling in Masterton as a case study. Simulation of PM_{10} dispersion in Masterton for winter months during 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. A good comparison between model results and pollution levels is achieved. Assimilating local wind data into the meteorological component of the model improves the agreement between observed and modelled PM_{10}. However, some of the extreme concentrations are better simulated without wind assimilation. Source contributions and effects of emission reductions scenarios on pollution levels are examined. It is estimated that, during the smog periods, home heating contributes to around 70% of all ambient PM_{10}. The contribution of secondary particulates is also estimated. The results are consistent with the contribution of secondary particulates being less than 20% of the total during the smog periods. Results also suggest that the recently developed national inventories provide satisfactory inputs for modelling and should be appropriate for other urban areas in New Zealand. Further work is in progress to improve modelling as a more robust tool for policy assessment.

INTRODUCTION

Knowing source contributions to air pollution is essential to construct effective mitigation measures. Airshed modelling can be a useful tool for this purpose. As a case study, this report presents airshed modelling and analysis of source contributions for PM_{10} in Masterton. The contribution of secondary particulates is also estimated. Masterton, with an urban population of about 18 thousand, 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, in the urban area, PM_{10} exceedences of the national environmental standard

(NES) for ambient air quality (MfE 2004), which is a 24-hour average concentration of 50 μg m^{-3}. Therefore, reductions in emissions are required for NES compliance in 2013.

Air quality modelling is an essential tool for assessing mitigation options. Airshed modelling has not been carried out for this region. In this study, we use The Air Pollution Model (known as TAPM; see Hurley *et al.* 2005) 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 the providing better fields for dispersion modelling. It is run with and without this option. . A recent national inventory (Fisher *et al.*, 2005) is processed to provide model inputs, and model results are compared to air quality monitoring data. Emission reduction effects for NES compliance are assessed using the model.

MODEL CONFIGURATION

TAPM (Version 3) was run for the winter months May to August, 2003. 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-km, 10-km, 3-km and 1-km. The two innermost grids are shown in Figure 1. The corresponding dispersion model grids cover 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 above ground level. 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 simulates rain and snow processes. Default values of the other parameters were used.

A national PM$_{10}$ emissions inventory has been recently developed and used in the definition of New Zealand's local air management areas (LAMAs, or 'airsheds') (Fisher *et al.*, 2005). The Geographical Information System (GIS) based inventory includes industry emissions (point sources), domestic and vehicle emissions (presented as averages for the census unit area, 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 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 those CAUs with high domestic PM_{10} emissions (>10 kg/day/km^2) are highlighted. The inventory data were processed for input to TAPM, representing wood heater 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 an inert tracer in the model runs, which include a background concentration of 10 μg m^{-3}.

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 in Figure 4). Hourly PM_{10} concentrations (TEOM), wind speed, wind direction and temperature were measured at the Masterton site (Davy, 2003). In this study, the TEOM data are not corrected for the loss of volatile components from 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 NIWA climate database (CLIDB). The model was run in two modes: without wind data assimilation (NA) and with wind data assimilation (A). For the second run, the wind speed and direction data from the Masterton and East Taratahi sites were assimilated into the lowest model level (10 m) with 2 and 4 km radii of influence specified respectively.
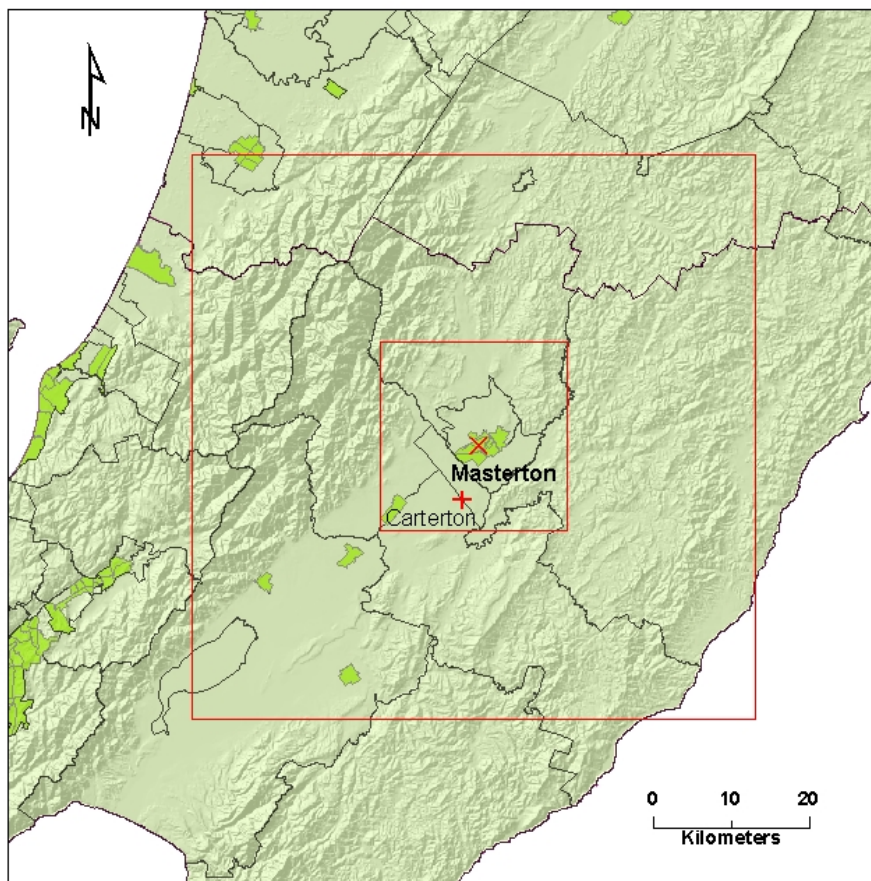
Figure 1. TAPM model domain (centre: $175^o38'$E, $40^o56.5'$S) for Masterton with nested Grids 3 and 4 displayed. CAUs with high domestic PM_{10} emissions (>10 kg/day/km^2) are shaded in dark green. The Masterton ambient monitoring site at Wairarapa College ($\times$) and the East Taratahi meteorological site (+) are also displayed.

RESULTS

Model predictions of meteorology were extracted at the nearest grid points to the Masterton and East Taratahi sites on the 1-km, and of ground-level PM_{10} at Masterton 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 those frequently applied for model evaluations (e.g., Hurley *et al.* 2003), including the correlation (Corr) between observed (Obs) and modelled (Mod) values, arithmetic mean, standard deviation (Std), root mean square error (RMSE), index of agreement (IOA), Skill_V (= Std_Mod / Std_Obs, showing skill if

close to 1), Skill_R (= RMSE / Std_Obs, showing skill when less than 1) and robust highest concentration (RHC). The IOA varies between 0 (no agreement) and 1 (complete agreement) with values above 0.60 considered a good agreement between modelled and observed parameters. The RHC is a preferred statistic for the performance of simulating the high end of the concentration distribution. The maximum concentration may be an outlier, whereas the RHC is smoothed over the highest eleven concentrations. As a result, the RHC may be higher or lower than the maximum concentration.

The performance statistics, when compared with hourly wind speed, wind direction and temperature observations, and 24-hour moving-average PM_{10} measurements, are shown in Table 1. The moving average is used for 24-hour PM_{10} concentrations from hourly model outputs or measurements (TEOM data). Simulated wind speed agrees well with observations for both Masterton and East Taratahi sites, with IOA values greater than 0.7. Wind assimilation improves the modelled wind speed greatly, with IOA values = 0.91 for both sites, compared to ~ 0.75 without assimilation. The west-east (u) and south-north (v) components of wind speed also agreed well with observations. Results for temperature were excellent for both sites with IOA values greater than 0.85. There was a good agreement for simulated and measured PM_{10} concentrations, and also an improvement for modelling results with wind assimilation with IOA increasing from 0.62 to 0.66.

Figure 2 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 model is also able to simulate the dominant northeasterly and southwesterly winds (Figure 3). Wind assimilation also improves the results with comparison to without assimilation (not shown). For dispersion, light winds (inner parts of the wind roses, e.g., <3 m/s) are important. Assimilation improves results for calm conditions (<1 m/s). Observations 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. In the continuing work, some of the meteorological results will be re-

examined, particularly those for light wind and calm conditions, in order to reduce uncertainties in PM_{10} simulations.
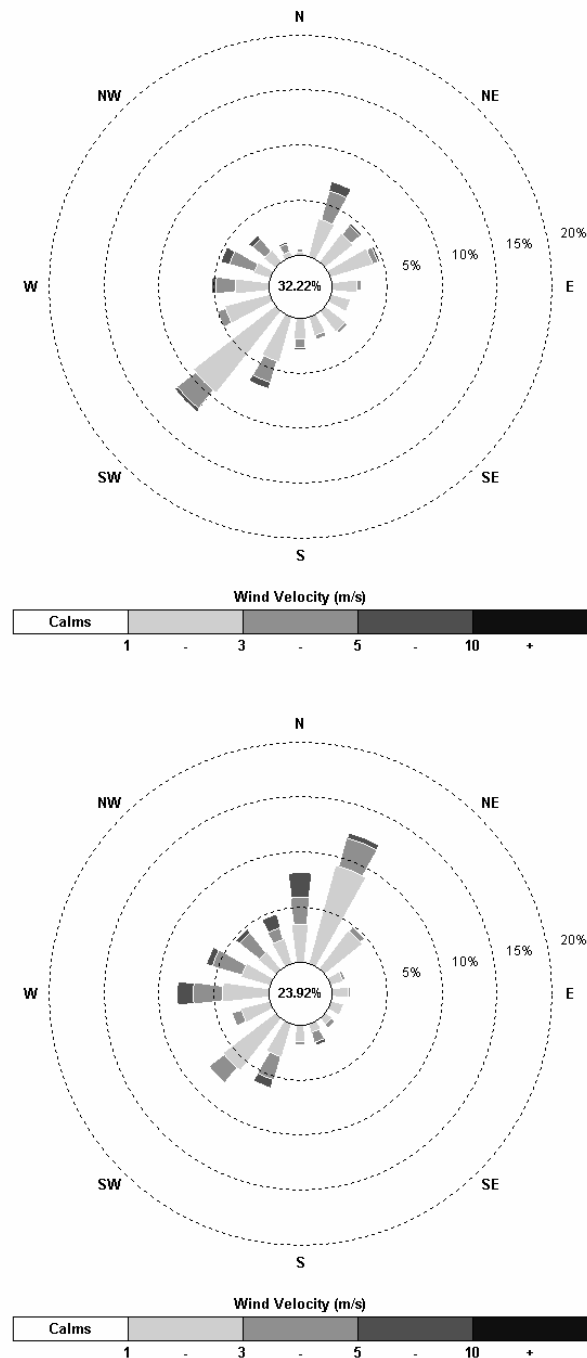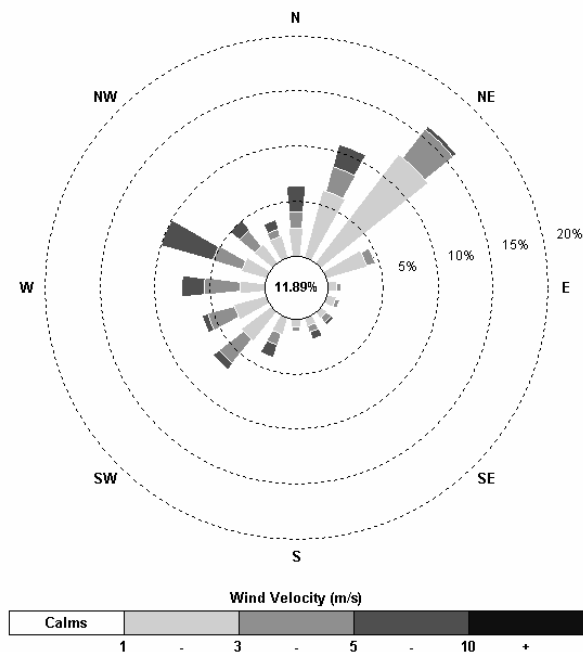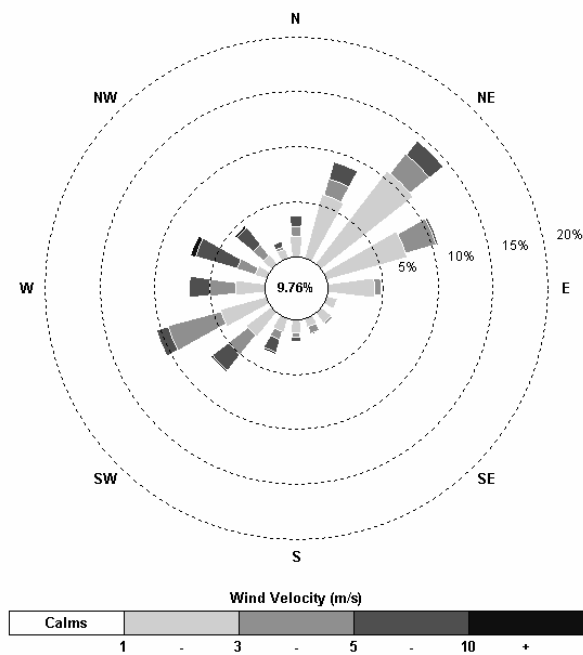

Figure 2. Wind roses of observed (top) and modelled (bottom, TAPM run with wind data assimilation) data for the Masterton monitoring site for May-August, 2003.

Table 1. Statistics for the TAPM simulation of May - August 2003 in Masterton*

Variable	No_Obs	Mean_Obs	Mean_Mod	Std_Obs	Std_Mod	Corr	RMSE	IOA	SKILL_V	SKILL_R
Wind speed (m s^{-1})										
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
West-east component (u) of wind speed (m s^{-1})										
Masterton_NA	2952	0.3	0.7	1.6	2.0	0.46	1.95	0.67	1.20	1.18
Masterton_A	2952	0.3	0.6	1.6	1.6	0.79	1.10	0.88	1.00	0.67
East Taratahi_NA	2705	0.6	0.7	2.8	2.7	0.58	2.50	0.76	0.95	0.90
East Taratahi_A	2705	0.6	0.7	2.8	2.5	0.86	1.44	0.92	0.90	0.52
South-north component (v) of wind speed (m s^{-1})										
Masterton_NA	2952	0.1	-1.3	1.7	2.5	0.68	2.28	0.72	1.45	1.34
Masterton_A	2952	0.1	-0.5	1.7	2.1	0.85	1.24	0.89	1.21	0.73
East Taratahi_NA	2705	-0.5	-1.1	2.4	2.6	0.75	1.89	0.85	1.10	0.79
East Taratahi_A	2705	-0.5	-0.8	2.4	2.4	0.91	1.06	0.95	1.02	0.44
Temperature (degC)										
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
PM$_{10}$ (µg m^{-3})										
Masterton_NA	2929	22.3	24.4	12.0	10.0	0.39	12.43	0.62	0.83	1.04
Masterton_A	2929	22.3	25.3	12.0	13.9	0.47	13.78	0.66	1.16	1.15

* TAPM was run without wind data assimilation (NA) or with data assimilation (A). Comparison was made for the Masterton site (wind speed, temperature and PM$_{10}$) and the East Taratahi site (wind speed, and temperature). See text for descriptions of statistical measures.

Figure 3. Wind roses of observed (top) and modelled (bottom, TAPM run with wind data assimilation) data for the East Taratahi meteorological site for May-August, 2003.

Assessing model performance for paired-in-time simulation 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 measurement). IOA values are greater than 0.60 (Table

1), with a factor-of-two of 0.80, for the two model runs. These results indicate that the model performs well for paired-in-time prediction, especially for the simulation with wind data assimilation (Hurley *et al.* 2003).
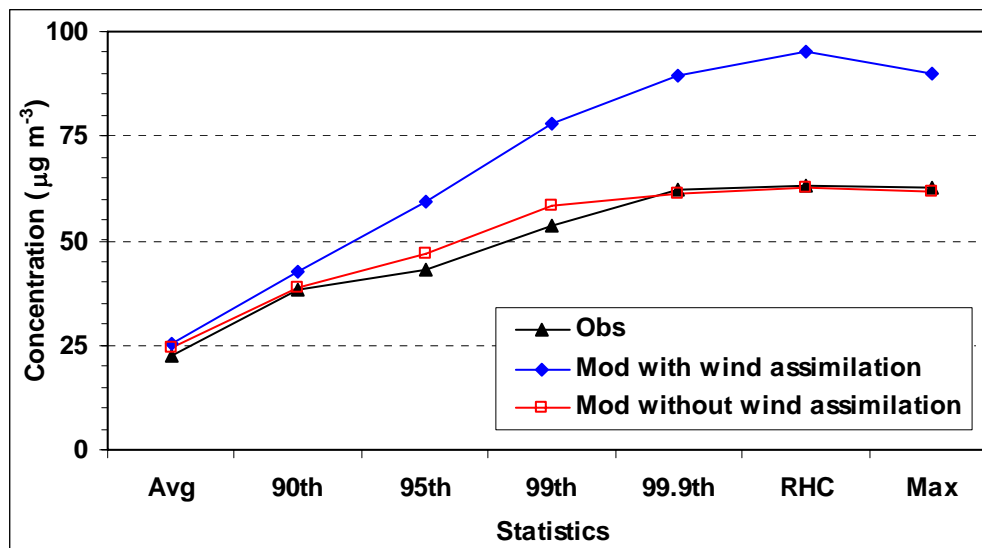
Figure 4. Statistics for observed (Obs) and modelled (Mod, with and without wind data assimilation) PM$_{10}$ concentrations at Masterton: average (Avg), 90th, 95th, 99th, 99.9[th], RHC and maximum (Max).

Figure 4 shows statistical measures of the high end of the concentration distribution. With assimilation, the model results in an over-estimate of PM$_{10}$ levels, while without assimilation the model is very close to observations. The observed RHC is 63 µg m^{-3}, compared to simulated values of 95 and 63 µg m^{-3}. When wind observations are assimilated into TAPM, introducing an apparent higher frequency of calms at this site, then the model simulation over-estimates for PM$_{10}$. Closer analysis of the wind data is being undertaken and we also note that this analysis and comparison is not conclusive since the actual PM$_{10}$ concentrations could be higher when the observed TEOM data are adjusted for the loss of volatile components.

SOURCE CONTRIBUTIONS

During smog periods (simulated moving 24-hour PM$_{10}$ concentrations equal to or greater than 50 µg m^{-3}) at the monitoring site, the most significant source is home heating, contributing to around 70% of the total ambient particulates (Figure 5)

(ranging between 62 and 74%, and 56 and 80% for the two model runs: without and with wind assimilation). Vehicle and industry account for about 9% and 5% respectively. There are emissions from other sources which are not available in the inventories, including sea spray, non-road dust and secondary particulates, contributing to approximately 16%.

The contribution of secondary particulates is not explicitly modelled and analysed in this study due to lack of emission data for gaseous pollutants. However, our results (Figure 5) indicate that secondary particulates contribute to less than 20% of pollution during the smog periods. Although secondary particulates may not be a major contributor to PM_{10}, their contribution to finer particle concentrations, e.g. $PM_{2.5}$, is usually higher. In addition, mitigation of secondary particulates requires reduction of precursor gases, for example, NO_x, SO_2, VOCs and NH_3. Therefore, the possibility of chemical processes leading to the production of secondary particulates needs investigation. This will be carried out using the chemistry module within TAPM when inventories for gaseous pollutants are available.
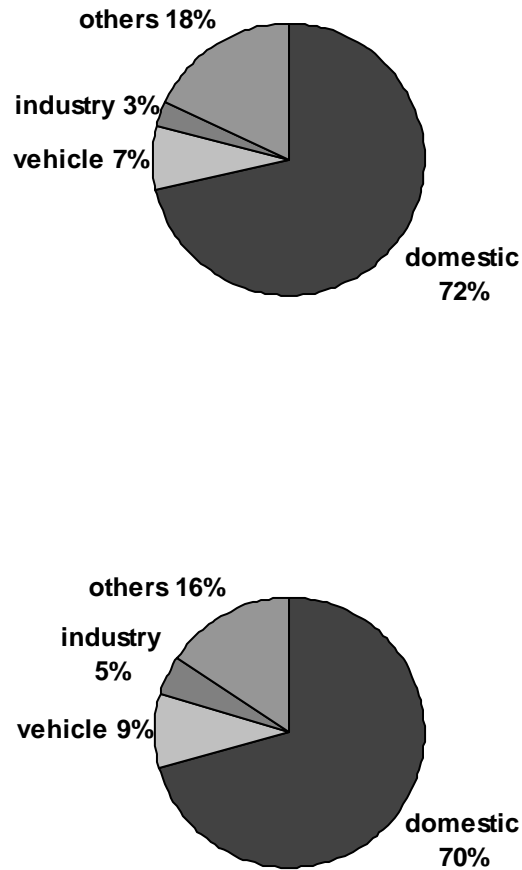
Figure 5. Source contributions during smog periods (modelled moving 24-hour PM_{10} concentrations equal to or greater than 50 µg m^{-3}) at the monitoring site. Top: TAPM run without wind data assimilation (116 exceedences). Bottom: TAPM run with wind data assimilation, sample size (116 exceedences). "Others" are sources not available in the inventories, including sea spray, non-road dust and secondary particulates.

EXAMINATION OF EMISSIONS REDUCTION SCENARIOS

The Wairarapa region contains Category 1, 2 and 3 LAMAs (Fisher *et al.*, 2005). In category 1 areas (the highlighted CAUs in Figure 1), PM_{10} exceedences currently occur, or are likely to occur without mitigation actions (that is, the maximum 24hour PM_{10} exceeds 50 µg m^{-3}). In category 2 and 3 areas, PM_{10} concentrations are currently

or likely below 50 µg m^{-3}. It is anticipated that only Category 1 LAMAs will require regulatory action at this stage. 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.

It is estimated that home heating contributes to about 70% of the pollution during smog periods (Figure 5). In Masterton, domestic PM$_{10}$ emissions in Category 1 LAMAs account for 78 % of total domestic emissions. Reduction of this portion of domestic emissions is expected to be the most cost-effective mitigation measure. Using the modelling output at the monitoring site, Figure 6 shows that a 35 % reduction results in 47 µg m^{-3} for the maximum concentrations, based on modelled results without wind data assimilation. However, a 70 % reduction is required to reduce the maximum concentrations to 46 µg m^{-3}, with the wind assimilation option, which once again shows the sensitivity of PM$_{10}$ estimation to the assessed frequencies of light winds and calms. This study demonstrates that modelling results can provide useful information for assessing effectiveness of mitigation measures. More emission reduction scenarios can be analysed with advice from the Regional Council.
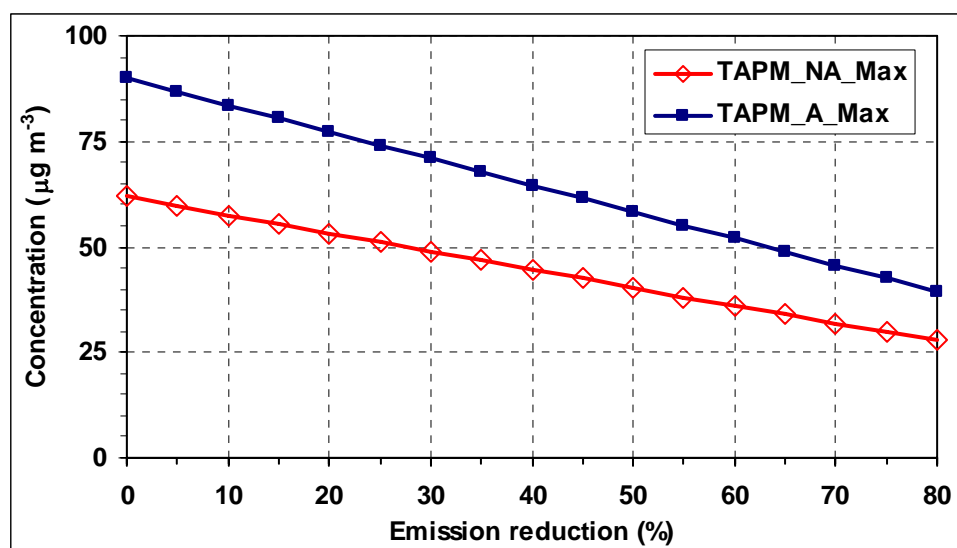
Figure 6. Response of the maximum moving 24-hour PM$_{10}$ concentrations at the monitoring site to reductions in domestic emissions in category 1 LAMAs. This is based on TAPM results with (TAPM_A_Max) and without (TAPM_NA_Max) wind data assimilation.

DISCUSSION AND IMPLICATIONS FOR NES ATTAINMENT

PM_{10} dispersion has been successfully simulated by using TAPM for Masterton for the winter of 2003. Statistical measures of model performance show that the model performs slightly better with wind data assimilation, except at the high end of the concentration distribution. This result supports the view that TAPM performs well without data assimilation (Hurley *et al.* 2003), and a major motivation for the development of TAPM was that it should work in the absence of local meteorological data. It is still advantageous to have some local data, for model validation.

According to Zawar-Reza *et al.* (2005), a lack of high quality emission inventories is the main limitation to progress in particulate modelling in New Zealand. A detailed inventory requires considerable resources to construct and is subject to uncertainty. Different approaches have been proposed for modelling input when a detailed inventory is not available or reliable. For example, it has been suggested that an inventory assuming a bi-Gaussian population distribution can be used for modelling urban nitrogen dioxide and ozone (Physick *et al.*, 2002). However, this approach is not suitable for simulating winter airborne particle pollution (Manins, 2005). The recent PM_{10} inventories for NZ (Fisher *et al.*, 2005), 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 much refinement (work on this is in progress). For Masterton, the inventory constructed in this way generates a satisfactory input for modelling. It is anticipated that the update version of the inventories will contribute significantly to the success of airshed modelling in NZ.

Our results show that modelling may be a useful tool for assessing emission reduction scenarios for NES compliance. They can also be used for studying human population exposure to particulate pollution.

There are two aspects of NES to which the modelling carried out here is relevant:
   (1) The Straight-Line Path, in which exceedences of PM_{10} concentrations should be decreased – *at least linearly* – so that they comply with the NES by 2013. For example, the number of exceedences of 50 $\mu g\ m^{-3}$ should decrease from

the current number to just one per year by 2013. A model is an essential tool in this evaluation, as it is being used for predictions under future conditions. The model links concentrations and emissions, and shows a close to linear relationship between them. Hence, emissions should be decreased – *also at least linearly* – to reduce the highest concentration below 50 $\mu g\ m^{-3}$ by 2013;

(2) Airshed modelling accounts for dispersion beyond the boundaries of the CAUs, and in the current work shows regions of concentration above 50 $\mu g\ m^{-3}$ outside the Category 1 CAUs of Masterton. It also shows regions within the Category 1 CAUs of Masterton which do not exceed the NES. However, this study is not aimed at redefining LAMAs based on modelled concentration. Maximum emissions and maximum concentrations can occur in different locations; policy decisions will be applied to emissions, to reduce concentrations below 50 $\mu g\ m^{-3}$.

Work is in progress to improve the modelling and its applications further. Source contributions to ambient PM_{10} will be approximated with incorporated natural sources, i.e., sea salt and dust, and a suitable aerosol chemistry module enabled. This, together with research of source apportionment in the area (Davy *et al.* 2005), will provide a more robust tool for policy assessment. Model runs will be carried out for several years to gain a better understanding of the important meteorological processes related to elevated PM_{10} concentrations.

ACKNOWLEDGMENTS

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