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Evaluation of Proposed Winter PM Concentration Reduction Strategies Using the MM5 and CAMx4 Modelling System - Christchurch, New Zealand, 2005–2013

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Abstract

Mesoscale Model (MM5) and Eulerian Comprehensive Air quality Model (CAMx4) were used to evaluate dispersion of particulate matter (PM) generated by "Total" emissions for Christchurch (New Zealand) for winter 2005. "Total" emissions consist of the "Domestic", "Transport" and "Industry" emissions. A composite chemical scenario generated from transport-related (day-time) and domestic-related (night-time) chemical scenarios was shown to be an optimal chemical split of input gridded emissions for predicting PM concentrations with minimal error when compared with ambient data. Reduction of gridded emissions of fine ($PM_{2.5}$) and total (PM_{10}) aerosol from domestic and transport sources can be achieved by linear reduction of the PM emissions in the emissions groups, as well as by non-linear reduction in the groups by varying the percentage of each chemical component of the scenario used to chemically split the PM input gridded emissions. Results of comparison of the linear and non-linear reduction for winter 2005 heavy smog episodes support the reliability of the 1999 inventory. The predicted linear and non-linear reduced PM values belong to the same population with correlation coefficients of 0.88 to 0.98. Based on these results, a sequence of experiments has been conducted to evaluate the potential decrease of PM winter concentrations over the 2005–2013 time period, using proposed reduction of PM winter emissions (in both the "Domestic" and "Transport" groups) using the linear reduction scheme. Two different abatement strategies outlined by the New Zealand Ministry for the Environment (MfE) to reduce aerosol concentrations and to achieve compliance with the PM reduction plan (target year 2013) were studied numerically using proposed aerosol emissions reductions.

Keywords: MM5-CAMx4; PM_{10}; Complex chemical scenario; Linear and non-linear reduction; Christchurch; SLiP-CLiP.

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INTRODUCTION

The city of Christchurch is situated on the coastal edge of the Canterbury Plains in the South Island of New Zealand. It has significant wintertime air pollution that is dominated by smoke generated by domestic fires (Scott, 2005). The emissions consist mostly of fine particulate matter ($PM_{2.5}$) that represents about 75-85% of the total PM_{10} (Aberkane *et al.*, 2004). The "Total" group emissions consist of the "Domestic", "Transport" and "Industry" aerosol emissions with a dominant contribution from the domestic sector in the development of winter-time aerosol peak concentrations. A composite chemical scenario generated from transport-related (day-time) and domestic-related (night-time) scenarios (Titov *et al.,* 2007c) is considered to be an optimal one for accurately predicting concentrations of ambient PM.

The key aims of this research are:

- To check the reliability of the 1999 emissions inventory using 50% linear and non-linear reduction of PM emissions in the principal emission groups, and to verify that predicted ambient aerosol concentrations can be considered to come from the same general population (based on winter 2005 smog episodes);
- To undertake a sequence of experiments to predict future winter $PM_{2.5}$ and PM_{10} concentrations (over the 2005–2013 time period) using proposed reduction of winter PM emissions (Ministry for the Environment, 2003; Scott and Gunatilaka, 2004) in the "Domestic" and "Transport" groups applying the linear reduction method to input emissions calculated initially from the 1999 inventory.

THE CHRISTCHURCH AREA WINTERTIME METEOROLOGY

Christchurch has significant wintertime aerosol air pollution that is dominated by smoke generated by domestic fires burning fossil fuel during cold nights (Spronken-Smith *et al.*, 2005) and by secondary aerosol predominantly from vehicular exhaust systems (Senaratne *et al.*, 2005). PM emissions consist mostly of fine particulate matter ($PM_{2.5}$) that contributes about 75-85% of the total PM_{10} during wintertime pollution episodes (Aberkane *et al.*, 2004; Scott 2005). From winter 2005 observations $PM_{2.5}$ provided 78.9% of PM_{10} for a 45-day research period (1 May–15 June 2005) and 82.1% for May–July 2005 ($PM_{2.5}$ was not measured in August). A principal aim of this study is to investigate a proposed decrease of $PM_{2.5}$ (PM_{10}) ambient concentrations over the 2005-2013 time period using the MM5-CAMx4 numerical modelling system and an optimal chemical scenario used to split PM input gridded emissions for input to CAMx4 (Titov *et al.*, 2007c).

During winter time under anticyclonic stagnant synoptic conditions, strong near-surface temperature inversions increase the air pollution potential, resulting in high PM concentrations especially close to midnight when there is minimal near-surface ventilation (McKendry *et al.*, 2004). The winter season is characterized by frequent occurrence of severe nocturnal aerosol smog episodes and the WHO

health guideline (50 μg/m^3 daily) is exceeded 30-40 nights each winter (Aberkane *et al.*, 2004). Topographically induced local air circulation over the Christchurch region plays an essential role in the accumulation and dispersion of PM (Kossmann and Sturman, 2004). The development of local winds includes a thermally generated day-night (sea-land) breeze and nocturnal cold air drainage wind from the Canterbury Plains and Port Hills (McKendry *et al.*, 1986). Nocturnal drainage winds enhance the strength of the near-surface night-time temperature inversion (Jonhstone 2000; McKendry *et al.*, 2004). The dataset, including several in-town observational sites, obtained during the Christchurch Air Pollution Study 2000 (CAPS2000 – Kossmann and Sturman, 2004) was used to validate the MM5-CAMx4 numerical modelling system (Titov *et al.*, 2007b).

DESCRIPTION OF THE MM5 v3.7.3-CAMx4.2 MODELLING SYSTEM

MM5 MPP v3.7.3 is a fifth generation non-hydrostatic limited-area mesoscale model using a terrain-following sigma-coordinate system and up to 5 nested grids to simulate mesoscale atmospheric circulations. It was developed by the National Center for Atmospheric Research (NCAR) and University Corporation for Atmospheric Research (UCAR, Dudhia *et al.*, 2000). The Comprehensive Air quality Model (CAMx4.4) is a Eulerian photochemical dispersion model that is designed to unify all of the technical features required of 'state-of-the-science' air quality models into a single efficient system. CAMx4.4 simulates the emission, chemical reactions and removal of pollutants (ENVIRON, 2005). The combined MM5-CAMx4 numerical system provides advantages in predicting pollution dispersion over complex terrain, since the mesoscale model calculates surface layer meteorological fields, which are used as input-nudging ones to drive CAMx4.4 to estimate the dispersion of aerosol air pollution. Maps of the location of the city of Christchurch and the MM5 four grids with spatial resolutions of 27, 9, 3 and 1 km are presented in Fig. 1. The coarsest resolution grid covers nearly all of New Zealand, while the 4th grid covers just the Christchurch area. Topography and land-use distribution were obtained from the USGS global database with a spatial resolution of 30 seconds. NCEP/NCAR re-analysis global data were used for initialization and nudging of MM5 during each run.

The Christchurch gridded emissions data for $PM_{2.5}$ and PM_{10} have a resolution of 1 km and were prepared using a Geographic Information System for the "Domestic", "Transport" and "Industry" emission groups. To account for the diurnal variation in $PM_{2.5}$-PM_{10} emissions, the Christchurch "mean winter day" emissions from the 1999 inventory were split into four time intervals (6 am-10 am, 10 am-4 pm, 4 pm-10 pm, 10 pm–6 am) and the emission values in any grid point were constant within each time interval (Scott and Gunatilaka, 2004). Table 1 shows a temporal scenario obtained from the 2002 inventory and provides the distribution of percentage hourly emissions over a winter day

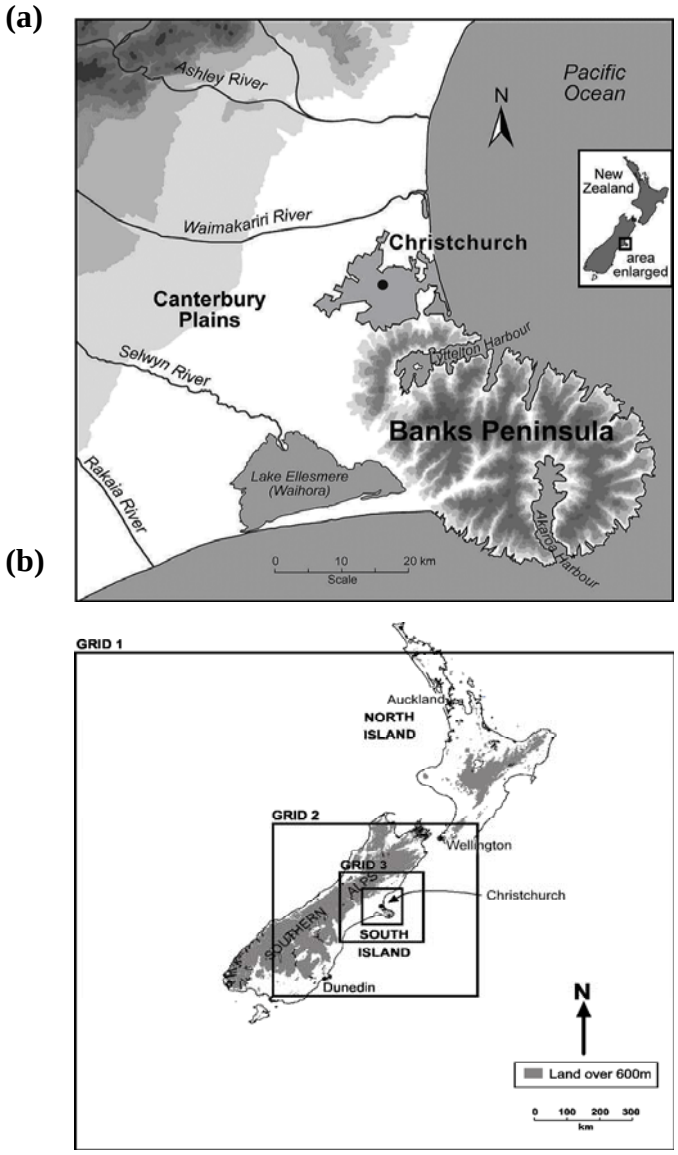

Fig. 1. (a) Location of the Christchurch region where the black dot represents the location of the Coles Place monitoring site; (b) the MM5 grid setup used in this study.

in the "Domestic", Transport" and "Industry" groups (Scott, 2005). It shows peaks of total aerosol emissions falling in daytime in the "Transport" (74.64%) and "Industry" (70.53%) groups and at evening-night-time in the "Domestic" group (68.63%). As described before, domestic emissions play the most important role in PM peak concentrations, and this temporal distribution (plus an additional contribution from the evening rush hour transport emissions) pre-defines a dominance of the night-time aerosol peak associated with the local scale air circulation (based on 7 episodes in winter 2005). The four time periods defined during the 1999 inventory were replaced by the hourly changing emissions obtained from the 2002 inventory for every grid point and all three emission groups. This was done by applying the percentage data from Table 1 and the emissions data to every point of the group's

gridded emissions based on the 1999 emissions inventory. The only spatially detailed PM emission inventory produced by the local environment agency, Environment Canterbury, was that for 1996, which then formed the basis of the 1999 GIS based inventory. The later 2002 inventory provided data for only two sub-areas of the city (Scott, 2005). The spatial distribution was therefore based on that of the 1999 emissions inventory, while the temporal 24-hour variation at each point was obtained by applying the percentages from Table 1. The optimal chemical split of the PM_{10} and $PM_{2.5}$ emissions was selected as a result of the evaluation of several chemical scenarios composited on the basis of the accumulated

Table 1. Distribution of percentage hourly emissions through the day for "Domestic", "Transport" and "Industry" groups (after Environment Canterbury, Scott, 2005).

Hour ending	Domestic	Transport	Industry
1	3.5%	0.61%	2.0%
2	3.5%	0.50%	2.0%
3	3.5%	0.80%	2.0%
4	3.5%	1.29%	2.0%
5	3.7%	1.62%	2.0%
6	3.6%	1.93%	2.0%
7	4.6%	4.22%	8.0%
8	3.9%	6.86%	8.0%
9	4.0%	6.17%	8.0%
10	3.9%	5.69%	8.0%
11	3.5%	5.68%	6.0%
12	3.0%	6.11%	6.0%
13	2.7%	6.34%	6.0%
14	2.2%	6.27%	6.0%
15	2.2%	6.47%	6.0%
16	2.3%	6.82%	6.0%
17	3.8%	7.22%	3.0%
18	7.4%	6.79%	3.0%
19	8.4%	5.73%	3.0%
20	8.0%	4.08%	3.0%
21	6.8%	2.91%	3.0%
22	4.9%	2.54%	3.0%
23	3.5%	1.98%	2.0%
24	3.5%	1.37%	2.0%
SUM	100.00%	100.00%	100.00%
Day: 7 am – 6 pm	31.37%	74.64%	70.53%
Night: 7 pm – 6 am	68.63%	25.36%	29.47%

experience of the local scientific community (in New Zealand), and resulted in the CAMx4.4 best fit chemical scenario described in Titov *et al*. (2007c).

MODELLING RESULTS

Evaluation of the 1999 inventory

A flow chart of the logical structure of the model experiment is presented in Fig. 2. A 50% reduction in emissions of fine ($PM_{2.5}$) and total (PM_{10}) aerosol in the "Total" group (proposed by ECan for winter 2005) from domestic and vehicular sources can be achieved in two ways:

1. A 50% linear reduction in emissions of fine ($PM_{2.5}$) and total (PM_{10}) aerosol from domestic and transport sources can be achieved by dividing (by a factor of two) the domestic and transport emissions from the Christchurch 1999 inventory (Scott and Gunatilaka, 2004). A linear reduction in the groups "Domestic' and "Transport" results in a linear reduction in the "Total" group. The procedure involves arithmetic manipulation of 2-dimensional arrays of gridded PM hourly emissions for all 24 hours of a winter day;
2. Non-linear reduction of the proposed "Domestic" emissions only (no change to transport emissions). For the night-time part (Titov *et al.*, 2006) of the optimal chemical scenario (7 pm to 6 am), the chemical split of particulate species was: EC (50%) = EC*0.75 given that domestic and transport emissions of EC are approximately the same magnitude (Scott, 2005); POC (50%) = POC/2; SOA (50%) = SOA/2; PSO_4 (50%) = PSO_4 (as PSO_4 is associated with industry only and industrial emissions were nearly the same for the years 1999 and 2005 – Table 2); PNO_3 (50%) = $PNO_3/2$; PNH_4 (50%) = $PNH_4/2$ (where EC is elemental carbon, POC is primary organic carbon, SOA is secondary organic aerosol, where P = particulate sulphate, nitrate or ammonia). Primary and crustal elements (mostly natural origin, Scott, 2005) remain unchanged as there is no serious land erosion, car fleet increase or any mining works in the Christchurch area. The particulate species listed above are the only particulate species (except particulate water) defined in the CAMx4 chemical mechanism (ENVIRON, 2005). Non-linear reduction of the proposed "Transport" emissions (included in "Total" emissions) for the day-time (7 am to 6 pm) part of the optimal chemical scenario (Titov et al., 2006) has the following chemical split: EC (50%) = EC/2; OC (50%) = OC/2; SOA (50%) = SOA/2; PSO_4 (50%) = PSO_4 (industry only); PNO_3 (50%) = $PNO_3/2$; PNH_4 (50%) = $PNH_4/2$, with primary and crustal elements unchanged.

Reduction of the input emissions by 50% was based on a proposed Environment Canterbury (the local environment agency) strategy of decreased emissions over the years 2005-2013 (Table 2), with total PM_{10} emissions for winter 2005 expected to be about 54% of the total emissions for winter 1999. The ratio 0.50 was therefore accepted for the "Total" group emissions (Table 2) and was used for linear reduction in the "Domestic" and "Transport" emission groups. It is important to stress that it is impossible to properly separate "Domestic" and "Transport" emissions (within "Total"

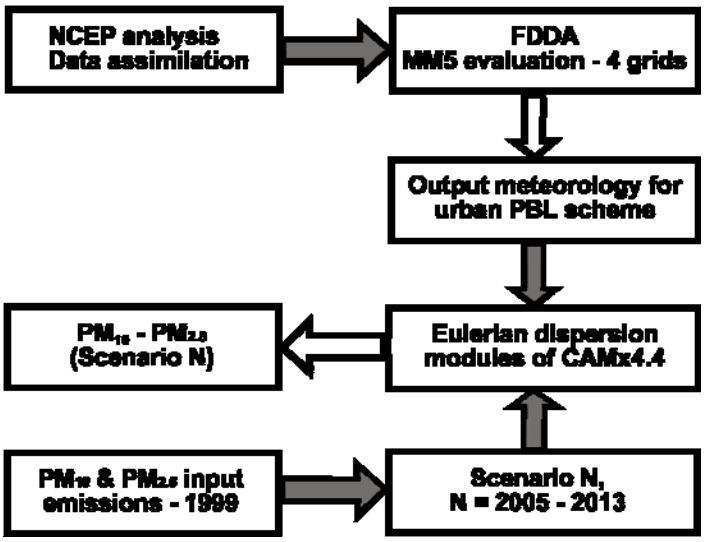

Fig. 2. Flow chart of the experimental numerical system. Input fields are indicated by filled arrows and output fields by empty arrows.

Table 2. Reduction of PM_{10} emissions (in grams/area-day, where area = 17,680 ha–city area) in the "Domestic" and "Transport" groups: 1999 compared to 2005, 2006, 2008, 2010 and 2013 winter seasons (Environment Canterbury proposed strategy, MfE, 2003).

YEAR	1999 kg/day	2005/1999		2006/1999		2008/1999		2010/1999		2013/1999	
		kg/day	%	kg/day	%	kg/day	%	kg/day	%	kg/day	%
Domestic Group	8341	4124.5	48	2974	36	1834.5	22	1457.5	17.5	998.5	12
Vehicular Group	1115	782	69	730	65	626	56	521	47	421	38
Industry Group	1027	1007	98.5	1026	100	1066	103	1105	108	1164	113
Total Group	10483	5913.5	54	4730	45	3526	33.5	3084	29.5	2584	24.5

emissions) in the case of the non-linear 50% reduction procedure, as several particulate species can originate from different emission groups (EC, OC, PNO_3). The dominance of "Domestic" emissions during night-time and "Transport" emissions during daytime (Titov *et al.*, 2007c) allows application of a non-linear 50% reduction to "Total" emissions during the half of the day when domestic activity dominates particulate production (7 pm to 6 am), and the other half when vehicular activity dominates (7 am to 6 pm). The "Industry" group emissions were unchanged, as industry emissions hardly changed between 1999 and 2005 (Table 2).

Inter-comparison of the linear and non-linear approaches will allow evaluation of the quality of the 1999 emissions inventory for all 3

emission groups if it is shown that modelled total $PM_{2.5}$ and PM_{10} concentrations for linear and non-linear reduction methods belong to one general population. The null hypothesis (that the two samples of PM concentrations belong to the same population) is applied to the 50% non-linear and linear emissions reductions in the "Transport", "Domestic" and "Domestic + Transport" groups for 7 smog episodes in winter 2005. Table 3 presents the ratio between reduced and initial (1999) concentrations, Pearson correlation and Spearman rank test (level of reliability) for linear and non-linear reduced fine and total PM concentrations in the groups "Domestic", "Transport" and "Domestic + Transport".

Pearson correlation and Spearman rank test statistics were applied to modelled PM (Table 3) to indicate whether the two different approaches to emissions reduction produce aerosol concentrations from the same population. From Table 3 it is evident that the linear and non-linear reduced ambient concentrations associated with the "Domestic" and "Transport" emissions reduction belong to the same population with a significance level $0.01 < P < 0.05$. The results supported the quality of the 1999 emission inventory, and provided confidence in the use of a linear reduction of emissions to investigate the possible impact of proposed reductions of $PM_{2.5}$ and PM_{10} emissions over the years 2005-2013 (Table 2). The meteorology from seven smog episodes in winter 2005 was used to provide the basis for this investigation.

Fig. 3 represents the spatial distribution of modelled PM_{10} concentrations (the optimal chemical scenario was applied to chemically split the gridded input emissions) for peak night-time PM_{10} concentration (11 pm on 4

Table 3. Reduced PM concentrations divided by 1999 inventory values, Pearson correlation and Spearman rank test: linear and non-linear reduced modelled PM in groups "Domestic", "Transport" and "Domestic + Transport" (7 winter 2005 smog episodes). The two numbers show the range of values for the seven events.

GROUP	DOMESTIC		VEHICULAR		DOMESTIC + VEHICULAR	
Reduction scheme	Linear	Non-linear	Linear	Non-linear	Linear	Non-linear
PM_{10} (50%) / PM_{10}	0.49–0.59	0.52–0.63	0.78–0.90	0.78–0.88	0.45–0.53	0.46–0.57
Pearson correlation (PM_{10} linear - PM_{10} non-linear)	0.84–0.94	0.84–0.94	0.89–0.96	0.89–0.96	0.89–0.97	0.89–0.97
Spearman rank test P (significance)	< 0.05	< 0.05	< 0.01	< 0.05	< 0.01	< 0.01
$PM_{2.5}$ (50%) / $PM_{2.5}$	0.51–0.61	0.56–0.68	0.80–0.94	0.80 –0.92	0.46–0.55	0.47–0.58
Pearson correlation ($PM_{2.5}$ linear - $PM_{2.5}$ non-linear)	0.78–0.94	0.78–0.94	0.88–0.97	0.88–0.97	0.90–0.99	0.90–0.99
Spearman rank test P (significance)	< 0.05	< 0.05	< 0.01	< 0.05	< 0.01	< 0.01

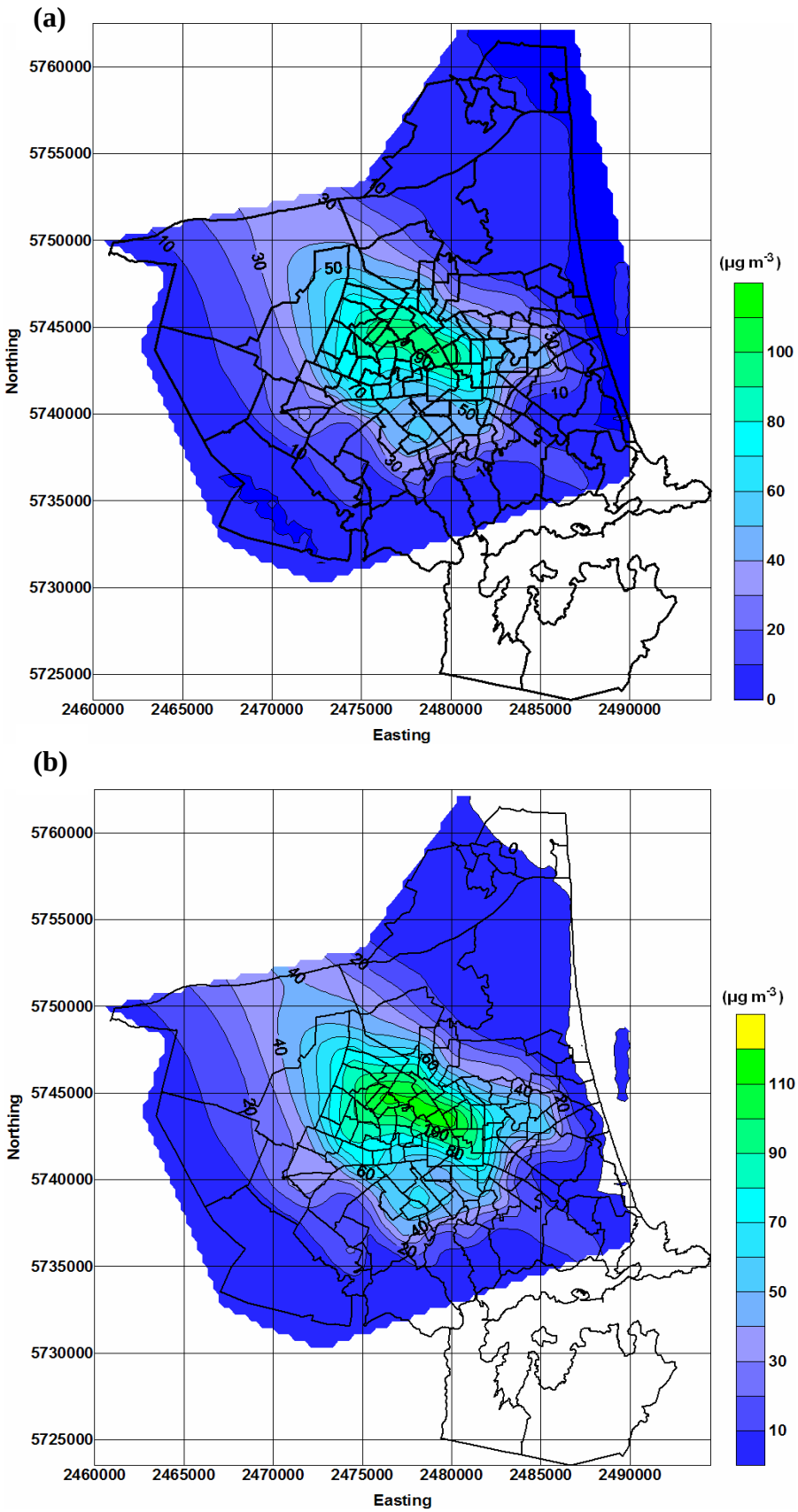

Fig. 3. Spatial distribution of "Total" PM_{10} (μg/m^3) at 11 pm 4 May 2005 using the optimal chemical scenario: (a) ("Domestic + Transport")/2 – linear; (b) ("Domestic + Transport")/2 – non-linear.

May 2005), showing similar PM_{10} spatial patterns for linear (Fig. 3a) and non-linear (Fig. 3b) 50% reduction of "Domestic + Transport" input emissions prepared for urban Christchurch.

Influence of emissions groups on a proposed future PM scenario

The effects of a proposed linear decrease of aerosol emissions in the "Domestic" and "Transport' groups and some increase in the "Industry" group (see Table 2) were evaluated using winter 2005 meteorology and decreased $PM_{2.5}$ and PM_{10} emissions combined into the "Total" group (over the 2005-2013 time period). The proposed reduction of $PM_{2.5}$ and PM_{10} emissions for the "Total" group for 2005-2013 (expressed as a proportion of the 1999 value) were calculated from Table 2 and are presented in Table 4. The decrease of average $PM_{2.5}$ emissions had a tendency to be faster than PM_{10} after year 2007 (Table 4). This is associated with a slower reduction (or no reduction at all) of the coarse $PM_{10-2.5}$ emission fraction (crustal elements and soil-dust particles), which has mostly a natural source.

The MM5-CAMx4.4 numerical modelling system was evaluated for 7 winter 2005 smog episodes. The CAMx4.4 maximum model run time was 72 hours, which is the typical synoptic time scale of a winter pollution episode for the Christchurch area. Fig. 4 presents the spatial distribution of predicted PM_{10} concentrations based on a proposed reduction of 70% (see Table 5) of the "Total" emissions for winter 2010 (Fig. 4a) and winter 1999 (Fig. 4b) based on "Total" emissions from the 1999 inventory. The proposed (by Environment Canterbury) 70% reduction of PM emissions is considered to be achieved in the "Domestic" and "Transport" groups only. This proposed PM reduction includes primary and secondary aerosol components. The example in Fig. 4 is typical of the midnight heavy smog episodes that are based on winter 2005 meteorology for the city of Christchurch. The maximum modelled hourly PM_{10} concentration for the proposed winter 2010 70% reduction of total emissions was about 70 $\mu g/m^3$ (Fig. 4a) compared with more than 440 $\mu g/m^3$ (Fig. 4b) obtained from the initial (winter 1999) total emissions. The modelled hourly PM_{10} concentration (peak time) is therefore predicted to decrease by more than 6 times, reducing the short-term exposure of local inhabitants.

Table 4. Proposed changes in the "Total" $PM_{2.5}$ and PM_{10} emissions group over the 2005-2013 time period expressed as proportions of the 1999 values (Scott, 2005).

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013
$PM_{2.5}$ (year) /$PM_{2.5}$(1999)	0.54	0.43	0.37	0.31	0.27	0.24	0.21	0.19	0.17
PM_{10} (year) /PM_{10} (1999)	0.53	0.42	0.37	0.33	0.30	0.27	0.24	0.22	0.21

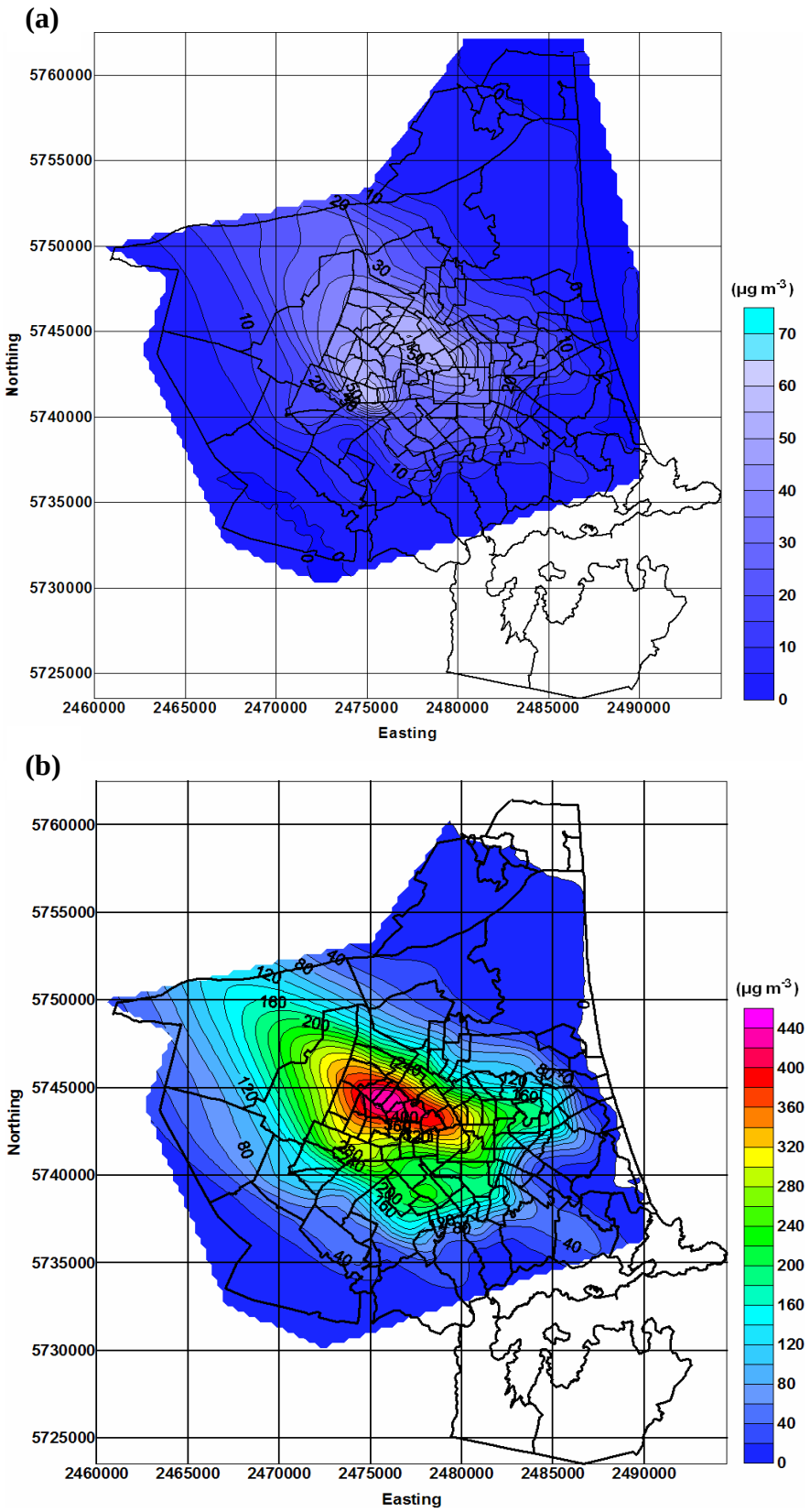

Fig. 4. Spatial near-surface (8-10 metres) distribution of PM_{10} concentrations (μg/m^3) at midnight 5 May 2005: (a) for the winter 2010 proposed 70% reduction of total emissions; (b) for the initial winter 1999 "Total" group emissions.

The Environment Canterbury proposed future total aerosol reduction scenario for the 2005-2013 time period consists of both negative and positive changes of PM_{10} emission in the different emissions groups (calculated in grams per area of the city per day). The proposed PM_{10} emissions decrease for a winter day in the groups "Domestic" and "Transport" and slight increase in the group "Industry" (grams/area-day, where area of Christchurch city = 17,680 ha, Scott, 2005) is presented in Table 5 (Ministry for the Environment. 2003).

It could be inferred from Table 5 that emissions from the domestic group will reduce by more than 3 times up to the year 2007, and by 2013 will be just 12% of the initial 1999 emissions. Also, a very fast decrease is suggested in the "Transport" group: 40% reduction up to 2007, and more than 60% by the year 2013. A small increase is evident in the "Industry" group, presumably resulting from predicted industrial sector growth in Christchurch. The proposed reduction in the "Domestic" and "Transport" groups appears to be unrealistic, as the total number of old-style open-fires and log-burners (the "Domestic" group) has no steep decreasing tendency, and the total vehicle fleet (the "Transport" group) has a tendency to increase with a gradual replacement of the old cars by new ones, and with a tendency for the proportion of diesel cars to increase. The reasons for these trends are quite simple and apparent — energy prices keep increasing and householders just don't have enough money to heat their dwellings using electricity only, and second-hand cars (especially diesel cars) are very popular, being relatively cheap.

Using numerical modelling to investigate the effect of reducing PM input emissions over the years 2005-2013 (Table 2 and Table 5), it is important to analyse PM_{10} and $PM_{2.5}$ concentration ratios in the "Total" group for the

Table 5. Ratio of winter day PM_{10} emissions in the "Domestic", "Transport" and "Industry" groups (grams/area-day, Christchurch area = 17,680 ha) for 2005-2013 to the 1999 winter day emissions.

Group / Year	1999	2005	2006	2007	2008
Domestic	1.000	0.494	0.357	0.292	0.220
Transport	1.000	0.701	0.655	0.608	0.561
Industry	1.000	0.980	0.999	1.019	1.038
Total	1.000	0.564	0.451	0.396	0.336
Group / Year	2009	2010	2011	2012	2013
Domestic	0.193	0.175	0.156	0.138	0.120
Transport	0.514	0.467	0.421	0.399	0.378
Industry	1.057	1.076	1.095	1.114	1.133
Total	0.312	0.294	0.276	0.261	0.247

Table 6. Average aerosol concentration (Modelled versus Observed) (μg/m^3), Mean Absolute Error (MAE) (μg/m^3), Pearson correlation coefficient (PCC), and percentage of 1999 concentrations for total and fine PM (for "Total" emissions only).

Part 1. Modelled PM – winter 2005	Average		MAE	PCC	2005/1999 (%)
	Mod	Obs	Mod - Obs		
PM_{10} – 2005 total	31.75	39.50	16.15	0.71	80.3
$PM_{2.5}$ – 2005 total	29.25	37.75	12.65	0.68	77.5
Part 2. Modelled PM – winter 2007	Average		MAE	PCC	2007/1999 (%)
	Mod.	Obs.	Mod. - Obs.		
PM_{10} – 2007 total	20.70	39.50	27.10	0.61	52.4
$PM_{2.5}$ – 2007 total	18.55	37.75	19.65	0.63	49.1
Part 3. Modelled PM – winter 2010	Average		MAE	PCC	2010/1999 (%)
	Mod.	Obs.	Mod. - Obs.		
PM_{10} – 2010 total	14.25	39.50	33.75	0.51	36.1
$PM_{2.5}$ – 2010 total	13.05	37.75	29.05	0.60	34.5
Part 4. Modelled PM – winter 2013	Average		MAE	PCC	2013/1999 (%)
	Mod.	Obs.	Mod. - Obs.		
PM_{10} – 2013 total	12.05	39.5	41.25	0.48	22.2
$PM_{2.5}$ – 2013 total	8.70	37.75	34.15	0.55	20.5

key years 2005, 2007, 2010 and 2013 (Table 6). This analysis will provide a better understanding of the basic rates of reduction of modelled PM concentrations obtained from the MM5-CAMx4 output (Titov *et al.*, 2007a). The numerically obtained concentrations were converted to ratios (%), reducing effects of PM time trends, and were compared with the proposed decrease of emissions (Table 5). Table 6 presents modelled versus observed average aerosol concentration, mean absolute error (at the Coles Place observation site), correlation coefficient and the ratio of modelled to observed PM_{10} and $PM_{2.5}$, based on 7 winter 2005 meteorological episodes for:

Part 1: modelled PM_{10} and $PM_{2.5}$ in the "Total" group for 1999 and 2005 winter emissions;

Part 2: modelled PM_{10} and $PM_{2.5}$ in the "Total" group for 1999 and 2007 winter emissions;

Part 3: modelled PM_{10} and $PM_{2.5}$ in the "Total" group for 1999 and 2010 winter emissions;

Part 4: modelled PM_{10} and $PM_{2.5}$ in the "Total" group for 1999 and 2013 winter emissions;

From Part 1 of Table 6 it is apparent that there was no serious decrease of total (80%) and fine (77.5%) modelled average aerosol concentrations in spite of the proposed (and modelled) 50% reduction in "Domestic" emissions and, as a result of residential sector dominance, a nearly 44% reduction in the "Total" group (Table 5) for the year 2005. Part 2 of the Table 6 shows that there was a significant decrease for total (48%) and fine (51%) modelled average aerosol concentrations in response to the proposed (and modelled)

70% reduction in "Domestic" emissions and, as a result of residential sector dominance, nearly a 60% reduction in the "Total" group (Table 5) for the year 2007. Results from Table 6 suggest that there should be a 3-fold decrease of residential aerosol emissions and a nearly 50% reduction of vehicular emissions to cause a 50% reduction of average concentrations of PM_{10} and $PM_{2.5}$. This was true for modelled average aerosol concentrations only (long-term PM exposure), while for short-term exposure (night-morning peak PM hourly concentrations) a 50% decrease in the group "Transport" was sometimes enough to reduce the PM maximum 2-fold.

Part 3 of Table 6 demonstrated a more noteworthy decrease for total (64%) and fine (65.5%) modelled average (over 7 episodes) aerosol concentrations in response to a proposed (and modelled) 82% reduction in "Domestic" emissions and, as a result of residential sector dominance, a more than 70% reduction in the group "Total" (Table 5) for the year 2010. Part 4 of Table 6 showed a third considerable decrease for total (78%) and fine (79.5%) modelled PM average concentrations (for the year 2013) as a result of the proposed (and modelled) 88% reduction in "Domestic" emissions and, as a result of residential sector dominance, a 75% reduction in the "Total" group (Table 5). This was the first time that the proposed reduction of PM emissions (Table 2) was less than the level of the modelled PM average concentration decrease. From the 4 parts of Table 6 it is clear that a 3-fold decrease of the initial (year 1999) residential aerosol emissions and nearly 50% reduction of vehicular emissions was required to halve the average PM concentrations (Part 2, Table 6). However, modelled PM concentrations rapidly decreased from 2007 until 2013. After 2007 the decrease of average aerosol concentrations indicated a stable trend for total and fine PM, definitely improving winter-time long-term ambient air conditions.

It is also important to discuss the straight and curved line path (SLiPs & CLiPs) PM_{10} concentration abatement tools introduced by the Ministry for the Environment (Fisher *et al.*, 2005) to develop targets and to predict the compliance of aerosol pollution reduction strategies for the 2005-2013 time period. In Section 1.2 of the SLiPs and CLiPS discussion document (Fisher *et al.*, 2005) it is stated:

1. "Straight line paths (SLiPs) are defined in the AQNES amendments under Regulation 17 subclause (5) as *"… a straight line that – a. starts on the y-axis of a graph at a point representing, as at the relevant date, the extent to which the concentration of PM_{10} in the airshed breaches its ambient air quality standard; and b. ends on the x-axis of the graph at a point representing, as at 1 September 2013, the ambient air quality standard for PM_{10} in the airshed."* (Fisher *et al.*, 2005);
2. Curved line paths (CLiPs) are defined in the AQNES amendments under Regulation 17 subclause (5) as *"… a curved line that – a. starts on the y-axis of a graph at a point representing, as at 1 September 2005 or the date that the plan is publicly notified (whichever is the later), the concentration of PM_{10} in the airshed; and b. ends on the x-axis of the graph at a point representing, as at 1*

September 2013, the ambient air quality standard for PM_{10} in the airshed." (Fisher *et al.*, 2005).

The SLiP and CLiP tools are illustrated in Fig. 5. From the document extract it is apparent that there is no serious reason to apply the CLiP strategy and the rest of the document is dedicated to development of the SLiP concept only. However, from the previously described MM5-CAMx4.4 modelled output it was absolutely obvious that the SLiP abatement strategy was an unrealistic one for aerosol pollution reduction. The authors of the key strategy document just relied on linear statistical methods, including the box model through the rest of the document (Fisher *et al.*, 2005). However, 4-D dynamical variation of ambient air pollution reflects a non-linear N-dimensional system (where N tends to infinity) and would never comply with straight-line reduction. From Table 6, it is clear that numerically modelled PM proposed decreases (over the 2005-2013 time period) could follow the CLiP graphic only, with the PM pollution reduction gradient increasing after year 2006.

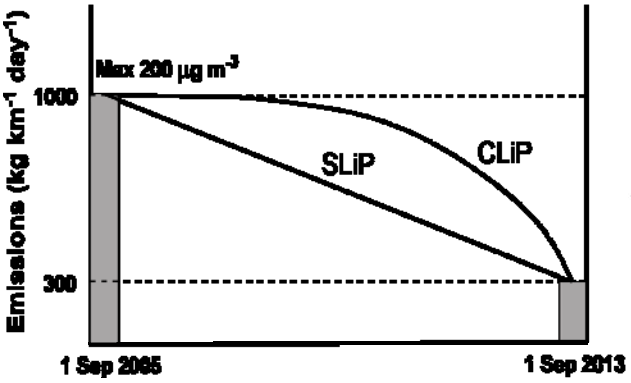

Fig. 5. Straight line path and curved line path examples (from Fisher *et al.*, 2005).

SUMMARY

A comparison of the effects of linear and non-linear emission reductions in the "Domestic"and "transport" groups for seven smog episodes in winter 2005 confirmed the reliability of the 1999 inventory, as the predicted linear and non-linear reduced fine and total PM concentrations appeared to come from one population ($0.01 < P < 0.05$, Spearman rank test) for all winter episodes. Based on these results, a sequence of experiments was run to calculate $PM_{2.5}$ and PM_{10} winter concentrations over the 2005–2013 time period (Ministry for the Environment, 2003) using the proposed linear reduction of winter PM emissions in the "Domestic" and "Transport" groups, and a light increase in the "Industry" group. The linear reduction scheme appeared to be a valid substitution for the non-linear reduction scheme when evaluating the effect of proposed emissions decreases on predicted levels of PM concentration over the city of Christchurch.

Assessment of the proposed reduction in fine and total PM for the time period 2005-2013 on the basis of 7 smog episodes (winter 2005) was undertaken using the MM5-CAMx4.4 numerical modelling system. The proposed PM emissions reduction was obtained from Environment Canterbury (Scott, 2005). It was apparent from modelled concentrations of total and fine PM (for the "Total" group) that it was enough to reduce vehicular emissions by 50% to decrease aerosol peak hourly concentration by 2-3 times (affecting short-term pollution exposure). However, for a decrease in long-term PM exposure more radical abatement

strategies should be applied. The winter aerosol abatement strategies would potentially lead to a considerable decrease of average fine and total PM concentrations (3-4 times) over 5-6 years, but would demand a significant reduction of "Domestic" and "Transport" emissions.

REFERENCES

Aberkane, T., Harvey, M. and Webb, M. (2004). *Annual* air Quality Monitoring Report 2003, *Report No. U04/58* 2004, Environment Canterbury, Christchurch, New Zealand.

Dudhia, J., Grell, G.A., Guo, Y., Manning, K., Wang, W. and Chiszar, J. (2000). PSU/NCAR Mesoscale Modelling System Tutorial Class Notes and User's Guide: MM5 modelling system Version 3, *Mesoscale and Microscale Meteorology Division*, NCAR, Boulder, Colorado, USA.

ENVIRON International Corporation (2005). CAMx, Version 4.4, Novato, California.

Fisher, G., Kuschel, G. and Mahon, K. (2005). *Straight and Curved Line Pathes (SliPs & CliPs): Developing the Targets and Predicting the Compliance, Discussion, Methodology and Example: a Report to Regional Councils.* SliP and CliPs Discussion Document, NIWA, Wellington, New Zealand, 27p.

Jonhstone, S.J. (2000). *The Interaction of Inversion Development and Katabolic Winds: Implications for Air Pollution in Christchurch,* MSc Thesis, Department of Geography, University of Canterbury, Christchurch, New Zealand.

Kossmann, M. and Sturman, A, (2004). The Surface Wind Field During Winter Smog Nights in Christchurch and Coastal Canterbury, New Zealand. *Int. J. of Climatology*. 24: 93-108.

McKendry, I.G., Sturman, A.P. and Owens, I.F. (1986). A study of Interacting Multi-scale Wind Systems, Canterbury Plains, New Zealand. *Meteorology and Atmos. Physics*. 35: 242-252.

McKendry, I.G.; Sturman, A.P. and Vergeiner, J. (2004). Vertical Profiles of Particulate Matter Size Distributions During Winter Domestic Burning in Christchurch, New Zealand. *Atmos. Environ.* 38: 4805-4813.

Ministry for the Environment (2003). *Regulatory Impact and Compliance Cost Statement: National Environmental Standards for Air Quality* 2003, Wellington, New Zealand.

Scott, A. (2005). *Source Apportionment and Chemical Characterisation of Airborne Fine Particulate Matter in Christchurch, New Zealand*. Unpublished PhD Thesis, University of Canterbury, July 2005.

Scott, A. and Gunatilaka, M. (2004). Christchurch Inventory of Emissions to Air, *Report N. R04, ISBN 1-86937-518-1*, Environmental Canterbury, Christchurch, New Zealand.

Senaratne, I., Kelliher, F.M. and Triggs, C. (2005). Source Appointment of Airborne Particles During Winter in Contrasting, Coastal Cities. *Aerosol Air Qual.* 5: 51–67.

Spronken-Smith, R., Sturman, A.P. and Wilton, E. (2005). The Air Pollution Problem in Christchurch, New Zealand, Progress and

Prospects. *Clean Air and Environ Qual.* 36: 23–28.

Titov, M., Sturman, A.P. and Zawar-Reza, P. (2006). A Comparison of Observed $PM_{2.5}$–PM_{10} Ratio with Values Modelled for Christchurch, New Zealand Using MM5-CAMx Numerical System: Different Chemical Scenarios and Associated Air Quality. *Air & Waste Manage. Assoc. 99th Annu. Conference*. New Orleans. 20-25 June 2006.

Titov, M. and Sturman, A.P. (2006). Application of the MM5-CAMx4.2 Numerical Modelling System to Investigate Different Ways of Reducing Aerosol Pollution from Domestic and Transport Sources: Christchurch, Winter 2005, Presentation at *Joint Conference Resource Management under Stormy Skies: Water Allocation @ the Crossroads?*, University of Canterbury, Christchurch, New Zealand. November 20-23.

Titov, M., Sturman, A.P. and Zawar-Reza, P. (2007a). Application of the MM5-CAMx4.2 Numerical Modelling System to Investigate a Proposed Reduction of Winter PM Concentrations in Christchurch, New Zealand Over the 2005-2013 Time Period, Extended Abstract. *Proc. of Air & Waste Manage. Assoc. 100th Annu. Conference*, Pittsburgh. 26-29 June 2007.

Titov, M., Sturman, A.P. and Zawar-Reza, P. (2007b). Application of MM5 and CAMx4 to Local Scale Dispersion of Particulate Matter for the City of Christchurch, New Zealand. *Atmos. Environ.* 41: 327–338.

Titov, M., Sturman, A.P. and Zawar-Reza, P. (2007c). Improvement of Predicted Fine and Total Particulate Matter (PM) Composition by Applying Several Different Chemical Scenarios: A Winter 2005 Case Study. *Sci. Total Environ.* 385: 284-296.

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