DISPERSION MODELLING OF PARTICULATE MATTER CONCENTRATIONS AT THE INTRAURBAN SCALE: EPIDEMIOLOGICAL APPLICATIONS

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INTRODUCTION

Epidemiological studies that assess the relationship between air pollution and adverse health effects typically utilise concentrations from one or few central ambient monitoring sites as a proxy for estimating personal air pollution exposure (*Samet, J.M. et al.*, 2000). In the case of particulate matter (PM), the common assumption is that concentrations are homogeneous and well correlated over an urban area, and thus, ambient sites are understood to be a valid substitute for personal exposures. However, recent research has highlighted the fact that this assumption does not always hold true at the intraurban (within-city) scale, leading to the potential for error in long-term epidemiological study designs (*Dominici, F. et al.*, 2003; *Wilson, J.G.*, in press). Hence, the development of models that accurately predict air pollution exposures at the intraurban scale has recently been recognised as a priority area of study (*Jerrett, M. et al.*, 2005). The aim of this paper is to evaluate the effectiveness of The Air Pollution Model (TAPM), for simulating small-area PM_{10} concentrations for the city of Christchurch, New Zealand. Air pollution has been a significant and persistent problem in Christchurch since the late 1800s and remains a considerable health risk to the current population (*McGowan, J.A. et al.*, 2002).

INTRAURBAN MODELLING OF PM_{10}

Jerrett, M. et al. (2005) recently reviewed intraurban exposure models, and highlighted that integrated emission-meteorological models (also known as mesoscale models or airshed models), which simulate the emission and dispersion of pollutants using coupled meteorological and chemical modules, offer promising potential for accurately estimating personal exposures. Although these models have been shown to be an accurate predictor of annual concentration levels at a single urban point (e.g., *Chen, F. and J. Dudhia*, 2001; *Hurley, P. et al.*, 2003; *Zawar-Reza, P. et al.*, in press), they have yet to be independently assessed at multiple and dense intraurban locations for use in epidemiological studies (*Jerrett M. et al.*, 2005). The most commonly used models are the Fifth Generation Mesoscale Model (MM5), and the Regional Atmospheric Modelling System (RAMS). Models like MM5 and RAMS have been used infrequently for exposure studies, mostly due to the high level of computing power and expertise needed to set up and run *long-term* simulations (*Jerrett, M. et al.*, 2005). The Air Pollution Model (TAPM) – has recently become available and has been designed for use by a wider non-specialist community. TAPM is a three-dimensional incompressible, non-hydrostatic, primitive equation model that uses a terrain-following coordinate system (*Hurley, P. et al.*, 2003). The model is a fast, closed-source, PC-based, prognostic and air pollution model with a Graphical User Interface (GUI) allowing for configuration of inputs.

METHODS

Physical setting

Christchurch is a coastal city on the South Island of New Zealand with a population of 320,000, located on the Canterbury Plains about 70 km east of the Southern Alps (172ºW, 43ºS) and just north of eroded remains of a late Tertiary volcanic complex known as Banks Peninsula or the Port Hills (Figure 1). The interactions between meteorology and topography in Christchurch are complex, providing a challenging environment for mesoscale models. Christchurch's mid-latitude location means that the climate is significantly influenced by the interaction between the eastward propagating high and low pressure systems and the Southern Alps massif. Superimposed on this flow are smaller scale thermally forced circulations caused by land-sea discontinuity and the sloping terrain of the Southern Alps and Port Hills.

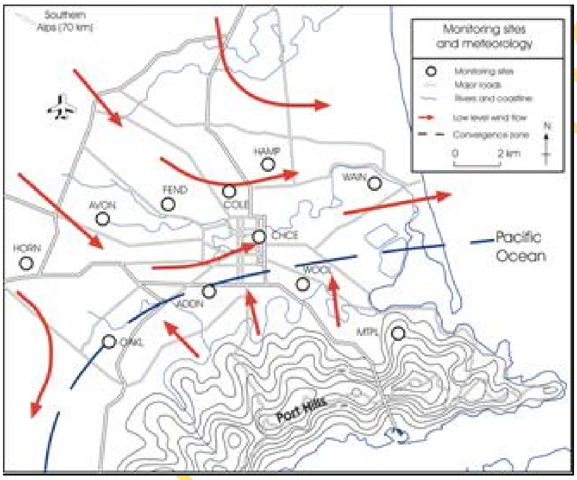

Figure 1 Local topography, meteorology during pollution episodes and location of monitoring sites (adapted from Kossmann, M. and A.P. Sturman, 2004).

Christchurch's high pollution concentrations each winter are due primarily to domestic heating emissions from the combustion of solid fuels into a nocturnal surface-based inversion layer. On average, 30 exceedances of the 50 µg m^{-3} 24-hour guideline occur each winter. Cold air drainage from the Southern Alps converging with more localised cold air drainage winds originating from the slopes of Port Hills is thought to generate zones of stagnant air, enhancing the strength of temperature inversions on cold winter nights (*Kossmann, M. and A.P. Sturman*, 2004).

Monitoring network and TAPM setup

To investigate the spatial heterogeneity of PM_{10}, a temporary PM_{10} monitoring network consisting of 11 Airmetrics MiniVol portable gravimetric samplers was operated over two winter months (July 2003 and June 2004) across the city. Selection of the monitoring site locations was based on established US Environmental Protection Agency (US EPA) criteria. TAPM was configured and run for the same duration as the monitoring network using three telescoping grids with 60 grid nodes in the latitudinal and longitudinal directions. The distance between the grid nodes was 13.5, 3.5, and 1.5 km. The coarsest resolution grid accounted for the whole of the South Island, while the high-resolution mesh was set to cover Christchurch and most of the Canterbury Plains, allowing for the simulation of local wind systems. To improve the simulated meteorological field over Christchurch, data assimilation was performed. Wind direction and speed were assimilated into the model from the Coles Place monitoring site (COLE). The zone of influence for the assimilated data was set for a 5 km radius with a relatively strong forcing of 0.8. A gridded PM_{10} emission inventory for Christchurch is used as an input into TAPM; details can be found in *Zawar-Reza, P. et al.* (in press).

Data analysis

Daily averages from monitored data were compared with 24-hour averages extracted from the corresponding TAPM grid cells. To assess the agreement between the model and the monitored data, Index of Agreement (IOA) was calculated according to *Willmott, C.J.* (1981). The IOA is a measure of skill of the model in predicting variations about the observed mean; a value above 0.5 is considered to be good. A coefficient of divergence (COD) was utilised to describe relative intraurban uniformity, defined mathematically in equation (1):

$$COD_{jk} = [\frac{1}{p}\sum_{i=1}^{p}[(x_{ij}-x_{ik})/(x_{ij}+x_{ik})]^2]^{1/2} \qquad (1)$$

where x_{ij} and x_{ik} represent the 24-hour average particulate concentration for sampling day i at sampling site j and modelled value k, and where p is the number of observations (*Wongphatarakul, V. et al.*, 1998). The COD is important as a relative measure of uniformity because high correlations between observed and modelled values demonstrate temporal homogeneity (i.e., values move up and down together), but may not necessarily describe concentration uniformity between predicted and observed values. A COD of 0 means there are no differences between modelled and observed concentrations, while a value approaching 1 indicates maximum differences and absolute heterogeneity.

RESULTS AND DISCUSSION

Table 1 displays the summary statistics for monitored and modelled data. There is a good agreement between the modelled and observed arithmetic mean of the eleven sites, and the mean minimum and maximum values.

Table 10 Summary statistics for winter monitoring and modelled data.

Site ID	Observed					Modelled				
	n	Mean ± SD*	Min*	Max*	Ex[1]	Mean ± SD*	Min*	Max*	Ex[1]	COD[6]
HAMP	59	47.8 ± 29.7	8.7	133.0	19	35.1 ± 30.0	2.1	114.6	16	0.44
CHCE	58	44.7 ± 29.4	6.8	148.9	20	64.4 ± 55.0	4.7	205.5	28	0.42
FEND	59	43.6 ± 26.3	11.0	132.8	19	59.1 ± 42.9	5.2	156.8	29	0.37
ADDN	59	49.3 ± 28.9	14.5	147.5	19	66.8 ± 50.8	5.2	188.0	32	0.37
WOOL	59	52.6 ± 33.2	13.7	171.3	23	46.5 ± 32.9	4.8	124.8	27	0.39
WAIN	59	48.6 ± 30.7	9.3	154.0	23	53.3 ± 39.8	5.8	144.5	28	0.36
AVON	58	40.5 ± 21.8	3.2	95.4	18	41.5 ± 30.5	6.7	122.7	20	0.34
OAKL	58	44.1 ± 26.7	11.2	167.2	18	20.8 ± 16.7	2.3	85.6	3	0.49
MTPL	59	16.3 ± 8.0	1.9	38.9	0	10.9 ± 7.5	1.9	35.1	0	0.42
HORN	59	41.7 ± 18.3	7.3	93.6	19	35.5 ± 23.9	6.6	104.6	14	0.33
COLE	59	53.6 ± 34.5	7.6	144.5	27	65.3 ± 51.9	4.8	189.5	32	0.40
MEAN	59	42.9 ± 25.3	8.8	128.3	18	43.4 ± 33.0	4.5	128.2	20	0.39

Key: *in $\mu g\ m^{-3}$. Ex[1] is the number of 24-hr average periods exceeding the ambient PM_{10} guideline of 50 $\mu g\ m^{-3}$.

The Mount Pleasant site (MTPL) had substantially lower observed and modelled maximums, probably due to its location on the Port Hills, where cold drainage flows transport most wintertime pollution towards lower elevations over the city. The number of exceedance days ranged from zero at MTPL for both observed and modelled data, to 27 observed exceedances at Coles Place (COLE) and 32 modelled exceedances at COLE and Addington (ADDN). The model underestimated high air pollution nights by as many as 15 nights at Oaklands (OAKL) and overestimated a maximum of 13 nights at ADDN with an observed mean of 18 nights over the guideline and a mean 20 exceedances for modelled data.

Figure 2 illustrates the IOA for PM_{10} at each station superimposed on modelled averaged concentration field. Generally, with the exception of MTPL, there is more agreement over central and eastern parts of the city than on the western fringes. Mean IOA for all sites is 0.60, with a minimum of 0.40 at MTPL. Sites on the western edge of the city yielded lower agreement with the model. The lowest IOAs were for MTPL, HORN, and AVON, which are either on the hills or the western fringes of the city. The IOA for wind speed, wind direction, and temperature at COLE is 0.63, 0.75 and 0.87 respectively, indicating that the model sufficiently defines the meteorology over the central urban area (note: these values are taken from a simulation *without* data assimilation; the IOA obviously increases with assimilation).

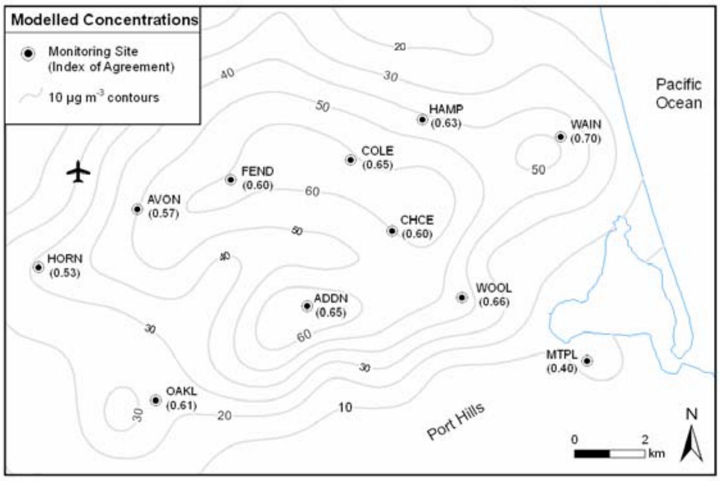

Figure 21 Contours of average modelled concentrations of PM_{10} and IOA over Christchurch, New Zealand, during July 2003 and June 2004.

While average modelled concentrations over the study period were found to be acceptable, daily statistical measures of observed and modelled values indicate that there is significant room for improved performance. A relatively high mean COD of 0.39 and substantial daily differences between modelled and observed data, along with the low correlations of daily values indicate that TAPM may not be an effective tool for estimating personal PM exposures in daily time-series studies under the settings described here (not shown). However, the more accurate long-term predictions indicate utility for longer-term cohort epidemiological study designs. The results of this study indicate that TAPM predicts medium- to long-term intraurban particulate concentrations with sufficient accuracy. Mean observed and modelled values differed by only 0.5 µg m^{-3} over the study period with a sufficiently high index of agreement (mean IOA = 0.60).

There are several factors that render the accuracy of the modelled concentrations particularly compelling. First, the particulate concentrations in Christchurch have been shown to exhibit considerable intraurban variability. In a recent study, the average COD between intraurban site concentrations (not between modelled and observed concentrations) in Christchurch (mean COD = 0.25) was shown to be significantly higher than in most large urban areas. The poor prediction capability of the model at the Oaklands and Addington sites is likely to be due to the misplacement of the convergence zone by the model (Figure 1). If mesoscale models prove to be successful at modelling intraurban concentrations in other cities, they may be a useful tool for studying the effects of long-term intra-community particulate exposure given the availability of a reasonably accurate emission inventory.

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