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Evaluation of a year-long dispersion modelling of PM_{10} using the mesoscale model TAPM for Christchurch, New Zealand

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Abstract

This paper examines the utility of The Air Pollution Model (TAPM; version 2) in simulating meteorology and dispersion of PM_{10} for 1999 over the coastal city of Christchurch, New Zealand. Christchurch usually experiences severe degradation in air quality during austral winter. The formation of a nocturnal inversion layer and the emissions of particulate matter (PM_{10}) mainly from solid fuel home heating appliances lead to severe smog episodes on an average of 30 nights during winter. The complex local topography surrounding the city in combination with influences from the urban areas can produce complicated boundary layer winds during quiescent weather. Simulated PM_{10} data are used for construction of annual exposure maps for the urban areas in order to assess the health impact of air pollutants due to chronic exposure (presented in an accompanying paper). Meteorology and PM_{10} dispersion results are statistically compared with the only permanent air pollution monitoring station available in order to evaluate the model's performance. Statistical measures such as the Index of Agreement (IOA) between modelled and measured data indicate that the model performs well. IOA is greater than 0.6 for meteorological variables, and various calculated skill scores place confidence in the model's performance. However, TAPM has a tendency to overestimate surface wind speed over urban areas during stagnant nocturnal conditions, resulting in quick flushing of pollutants.

Keywords: TAPM; Air pollution dispersion; Modelling; Exposure

1. Introduction

Internationally, New Zealand has a reputation for having a pristine environment with plenty of green spaces and lots of fresh, unpolluted air. However, in reality—at least as far as clean air is concerned—air pollution can be a serious problem in urbanized regions, especially during austral winter months. The coastal city of Christchurch, situated about 70 km east of the Southern Alps (172°37′ W–43°31′ S) and just north of a caldera (eroded volcanic crater) known as Banks Peninsula (Fig. 1), has a population of 300,000; occupies an area of about 140 km^2, and usually

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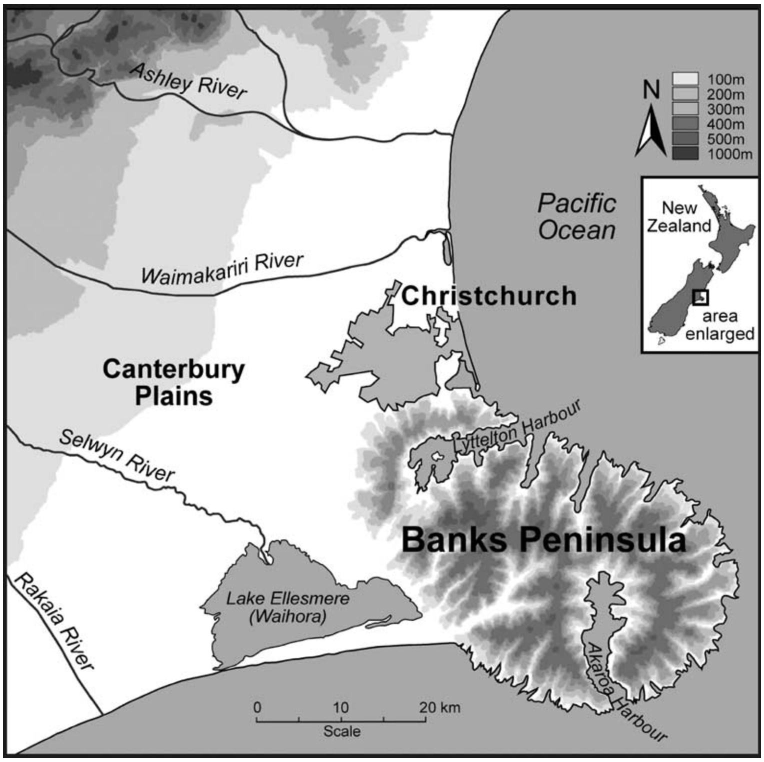

Fig. 1. Map of the Christchurch region. This map also is equal to the geographic extent of grid 3 in the TAPM simulations.

experiences smog events for about 30 days each winter season when the daily-averaged concentration of PM_{10} exceeds the air quality guideline of 50 μgm^{-3} (Aberkane, 2000). The area of Banks Peninsula just south of the urban area is known locally as the Port Hills.

The modelling work presented in this paper is part of an ongoing pilot programme to assess and evaluate air pollution exposure for selected urban areas in New Zealand (see www.hapinz.org.nz). A key component of this assessment is the construction of spatially detailed, annually-averaged air pollution exposure maps using an existing dispersion model. The exposure maps are needed in order, for example, to ascertain inequality in exposure to air pollutants between different social groups (Pearce et al., accepted for publication). Hence, there was a need for a computationally efficient meteorological model with an air pollution module. To this end, The Air Pollution Model (TAPM; Hurley, 2002) has been chosen. TAPM is a PC-based mesoscale prognostic numerical model with meteorological and air pollution components. The meteorological module of TAPM predicts the local-scale circulations, such as sea breezes and slope flows, in conjunction with larger scale synoptic scale meteorological fields.

Section 2 of this manuscript will provide an overview of meteorology of Christchurch, with particular emphasis on winter time smog episodes. In section 3, the derivation of pollutant emissions inventories used as input for TAPM is described in detail, while section 4 offers information on the TAPM setup and results.

2. Wind climatology of Christchurch

2.1. General

Christchurch is located in the mid-latitudes and its wind climate is largely controlled by eastward propagating high and low pressure systems and the city's geographic location relative to the Southern Alps (Sturman and Tapper, 1996). Over the Canterbury Plains, the synoptic scale wind is strongly modified by dynamic and thermal effects caused by the land–sea discontinuity, the Southern Alps and Banks Peninsula (McKendry, 1983). As shown in Fig. 2, synoptic scale westerly winds flow over and around the Southern Alps, resulting in frequent foehn winds (locally known as the nor'wester) and onshore north-easterly winds (McKendry, 1983; McKendry et al., 1987). In the initial stages of a westerly wind event, the convergence zone between the north-westerly foehn winds and the north-easterly onshore flow is present inland, whereas during the prefrontal final stage the convergence zone often tends to move out to sea. A period of cool south-westerly airflow is usually experienced in Canterbury after the passage of the cold front, until the build-up of a high pressure system. However, in some years, anti-cyclonic blocking to east of New Zealand can disrupt this pattern in August (Sinclair, 1996). The arrival of the next trough signals the restart of the sequence of wind changes. Superimposed on these synoptic scale wind are diurnal variations caused by the frequent development of easterly sea breezes during day-time (Sturman and Tyson, 1981), and night-time decoupling of the lowest air layers in which offshore drainage winds and land breezes are observed (McKendry, 1983; McKendry et al., 1986; Ryan, 1975). Large scale synoptic meteorology is accounted for in TAPM via grid nesting techniques—as described below.

2.2. Wind regime during smog episodes

Since the PM_{10} concentrations frequently reach high levels in winter, it is appropriate to briefly describe the meteorology during these episodes. The smog events usually occur during cold and calm nights when atmospheric stability and emissions (mostly from home heating and traffic) are high. According to Owens and Tapper (1977), synoptic climatology of such events revealed that situations with post-frontal south-westerly winds or with developing north-westerly winds aloft, or with weak easterly synoptic scale flows are favourable for the development of severe smog events. The near-surface airflow during smog nights is often dominated by westerly cold air drainage from the Southern Alps (Ryan, 1975), which might enhance the strength of the surface temperature inversion (Johnstone, 2000) and generate zones of stagnant air resulting from convergence with drainage winds down the slopes of Banks Peninsula (Fig. 3; Kossmann and Sturman, 2004).

3. TAPM grid setup and configuration

TAPM is a three-dimensional incompressible, non-hydrostatic, primitive equations model, which uses a terrain-following coordinate system (Hurley, 2002). For computational efficiency, it can be used in a telescoping nested configuration where higher reso-

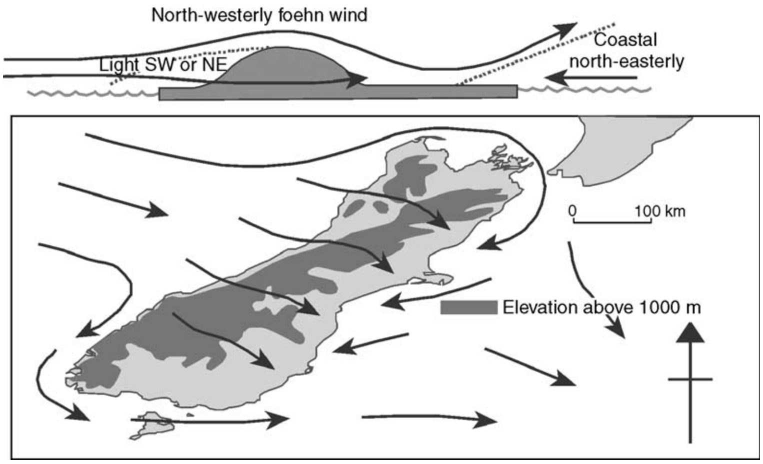

Fig. 2. Schematic of possible different flow patterns over the South Island.

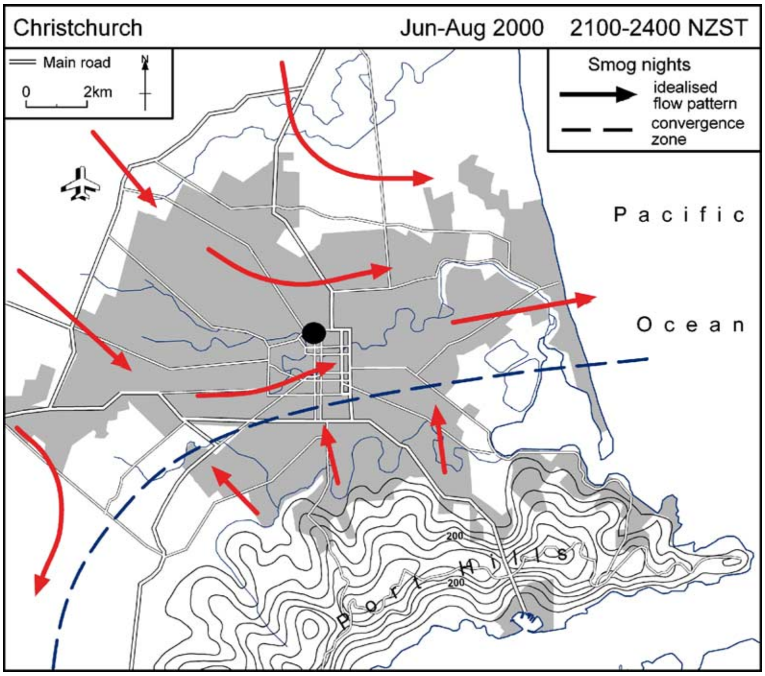

Fig. 3. Schematic illustration of the drainage flow pattern over Christchurch during smog nights, 2100-2400 NZST. The location of St. Albans monitoring site is shown by the filled circle (after Kossmann and Sturman, 2004).

lution grids are successively placed inside coarser resolution grids. In addition, model solution for each grid is one way interacting—information is passed from the coarse grid downwards. The meteorological component of the model is supplied with a dataset derived from the Limited Area Prediction System (LAPS) analysis data from the Australian Bureau of Meteorology (BoM; Puri et al., 1998), and takes into account the progression of eastward moving low and high pressure systems that were described in the previous section. The sea surface temperature is derived from Rand's global long-term means at a resolution of 100 km, although the prescribed values can be changed. Explicit cloud micro-physics option uses the scheme of Katzfey and Ryan (1997) for warm rain (ice processes are ignored). Short- and long-wave fluxes are calculated using Mahrer and Pielke (1977). TAPM is not suitable for representing deep atmospheric circulations due to the assumption of incompressibility and because non-hydrostatic effects only reach 5000 m, since above this level, the meteorological variables are smoothed out in order to minimize wave reflections from the model top. Therefore, TAPM is not suitable for simulating meteorology during strong westerly gradient flow which can cause deep wave activity. TAPM uses a gradient diffusion approach with a counter-gradient correction for turbulence closure. The diffusivity (K) is calculated with the standard E–ε scheme. The boundary layer adjacent to the ground is parameterized with the Monin–Obukhov surface similarity. Surface properties are accounted for with an energy balance scheme using the land-use and soil type as input. The scheme uses a single-layer canopy which does not resolve the flow within the canopy or the roughness sub-layer. Urban surface albedo (α_U=0.15), emissivity (ε_U=0.95), and anthropogenic heat flux (A_U=30 Wm^{-3}) are specified according to Oke (1988). An urban roughness length of 1 m is used to calculate the surface layer scaling variables.

The simulations presented here use three grids with grid spacing of 13.5, 4.5, and 1.5 km, respectively, with each grid having 60 zonal and meridional grid nodes. The largest grid covers all of the South Island of New Zealand (Fig. 2); grid 2 covers roughly the middle one third of the island; the geographical extent of grid 3 is the area shown in Fig. 1. To simulate the dispersion of PM$_{10}$, the air pollution module of TAPM was used in a tracer mode (with no chemistry). One tracer was allocated to represent emissions due to home heating with solid fuels (wood and coal) and the second tracer represents emissions from industry and the transport sector. The wood heater option of TAPM was used to treat the first tracer. In this mode, temperature corrections suggested by curve-fits according to Ng et al. (2000) are applied, resulting in adjustment of emissions due to home heating by taking into consideration the modelled daily-average temperature (e.g. emission is reduced on warmer days).

With this setup, meteorology and dispersion were carried out by TAPM for each month of 1999 separately. The limiting factor for the period of simulation is the size of the output files, which is dependent on the domain size. For each simulation, it takes TAPM about 12 h of simulated time to "spin-up" or dynamically adjust to topography, while at the lateral boundary of the coarsest grid, the model is constantly nudged towards the larger scale synoptic conditions (Hurley, 2002). The next section describes in detail how the PM_{10} emission inventories were obtained.

4. Derivation of PM_{10} emissions data

Emission inventory data has been collected in Christchurch on a regular basis to monitor trends over time and to determine changes in the relative contribution of sources to emissions (NIWA, 1998; Wilton, 2001; Scott and Gunatilaka, 2003). These present emissions to the air for a "typical winter's day" for the area within the Christchurch territorial boundary and comprised the main portion of the Christchurch airshed, as defined by Sturman and Zawar-Reza (2002). The inventory contains raw emissions data in kilograms or tonnes. The emissions are divided into four time periods: 6–10 a.m., 10 a.m.–4 p.m., 4–10 p.m., 10 p.m.–6 a.m. as well as 24 h total emissions. The inventories focus on emissions from domestic home heating, vehicle and industrial sources. In the 1999 emissions inventory Christchurch was separated into three different sub-areas; Inner Christchurch, Suburban Christchurch and Outer Christchurch. Inner Christchurch includes 44 Census Area Units (CAUs), Suburban Christchurch includes all suburbs within Inner Christchurch and an additional 42 CAUs and Outer Christchurch includes the remaining 31 CAUs outside Suburban Christchurch and within Metropolitan Christchurch (Wilton, 2001; Scott and Gunatilaka, 2003).

4.1. Domestic sources

Domestic home heating emissions were estimated by applying emission factors to home heating activity data. The collected activity data included number, type and age of appliance, and type and quantity of fuel consumed. Home heating activity and fuel use data were primarily collected through a survey of 1701 households (Lamb, 2000). The telephone survey compiled information on methods of home heating, volume and types of fuel used, fuel sources and frequency of appliance operation. Householders who used solid fuel heating methods were also invited to participate in a diary panel. Burning behaviour was monitored by participants on a day-to-day basis for a 2-week period. Wood burners were classified by installation date (pre-1992, 1992–2000, 2001–2002) to take into account changes in allowable emission limits over time. Emissions were calculated based on the fuel used by each appliance group and the corresponding emission factor. Emission factors were applied to the activity data to estimate the quantity of emissions from each source. Emission factors are representative values, which provide a representative measure of contaminant discharge for a specific type of activity and fuel consumption (Stern et al., 1992; Dasch, 1982).

4.2. Traffic sources

The calculation of motor vehicle emissions involved the collection of data on vehicle kilometres travelled under different levels of congestion, and the application of emission factors to these data. Emission factors were obtained from the New Zealand Traffic Emission Rates (NZTER) database using the national vehicle fleet weighted average data (MoT, 1998). Emission factors for two types of road scenarios were used; "central urban" (for the inner city) and "suburban" (for all other areas). Vehicle kilometres travelled were further sub-divided into three different driving conditions (freeflow, interrupted and congested) based on likely levels of traffic congestion (these are known as levels of service categories). The vehicle kilometres travelled (VKT) per day within the study area were calculated using the road transport model TRIPS (for more information see www.trips.co.uk).

4.3. Industrial sources

New Zealand's 1991 Resource Management Act is a key part of legislation aimed at ensuring environmental sustainability (RMA, 1991). Part of the Act states that any process that contravenes the Act requires a 'Resource Consent' to do so, including the discharge of contaminants into the air. The authorities responsible for issuing resource consents in relation air discharges are Regional Councils. Activity data for industrial emissions were collected from resource consent files. All of Environment Canterbury's discharge to air consent files were examined and emissions from 585 activities were included in the 1999 industrial emissions assessment. For each industry, the different activity types resulting in discharges to air were identified and each treated as a separate discharge. The data included discharge activity, quantity of fuel used, type of control equipment, process factors that may influence emissions, daily hours of discharge and results of any stack emission testing. These data were used to calculate total emission by pollutant for each emission inventory area.

4.4. Spatial resolution

The data from the emission inventory is prepared at a fairly coarse scale (a population of over 300,000 is divided into three spatial areas). The data needed to be disaggregated to finer spatial units; in this case 117 CAUs. In the first instance the data were disaggregated to the finer spatial units used in the 1996 emissions inventory. In the 1996 inventory, data for Suburban Christchurch were sub-divided into 25 suburbs; 9 in the 1999 Inner Christchurch and 16 in Suburban Christchurch (Outer Christchurch remained as one unit) (Table 1) (NIWA, 1998). Supplementary data sources such as the 2001 census and vehicle-modelling data were then used to break down the emissions inventory data into the 117 CAUs.

Table 1
Spatial nesting of emissions inventory areas and census area units

1999 emissions areas	Inner Christchurch	Suburban Christchurch (not including Inner Christchurch)	Outer Christchurch
No. of 1996 areas (suburbs)	9	16	1
No. of CAUs	44	42	31

For domestic emission, census data relating to the type of fuel used to heat dwellings were used. Data were extracted from the census about the number of dwellings per CAU that burn wood and coal to heat their homes. From this, each CAU was assigned a percentage based on the number of dwellings per CAU that use these fuels to heat their homes out of the total number of dwellings for each of the three larger emissions inventory regions. The percentages were then used to break down the raw emissions data for the three large regions.

For traffic emissions, the 25 suburb emissions where broken down to census area units using 2001 vehicle kilometres travelled (VKT) data from the TRIPS model summarised for each census area unit.

For industrial emissions consent data was accessed through GIS databases and, using GIS the point source industrial emissions consent data were joined to the 2001 census area unit polygon map. This identified the census area unit each industry was located within. CAU emissions were then calculated by totaling the emission estimates from each industrial source for each CAU.

5. Results and discussion

Statistical measures, such as Root Mean Square Error (RMSE) and Index of Agreement (IOA) are used to evaluate TAPM's performance ($RMSE = \left[\left(\overline{P-O}\right)\right]^{1/2}$, and $IOA = 1 - \left[\left(\overline{P-O}\right)^2 / \left(|P-\overline{O}|+|O-\overline{O}|\right)^2\right]$; where the Predicted ($P$) values by the model are compared against Observed (O) data (Willmott, 1981). The IOA is a measure of the skill of the model in predicting variations about the observed mean; a value above 0.5 is considered to be good. The modelled data, at 10 m above the ground for wind and at screen level for temperature, were extracted from the closest grid point to the Environment Canterbury's St. Albans monitoring site (Fig. 3) and represent hourly averaged conditions for a grid volume whereas the observations are obviously hourly averaged conditions at a point.

Results presented in this paper are from TAPM's simulation of meteorology and dispersion of PM_{10} for 1999. As an example of the model's performance, wind roses constructed from observed and modelled data for the entire year are shown in Fig. 4. It is encouraging to note that the model is able to represent the two most common flow patterns over Christchurch, the southwesterly which is associated with the passage of cold fronts and the north-easterly which is associated with sea breeze effect and the formation of lee troughs (McKendry et al., 1986). However, TAPM underestimates the calm conditions by 11%. Calm conditions are prevalent most winter nights during settled anti-cyclonic synoptic situation. Instead of simulating calm conditions, TAPM frequently produces weak westerly (drainage) winds produced by the gently sloping Canterbury Plains and the Southern Alps (results not shown here, but see Zawar-Reza et al. (2005) for a more detailed evaluation). The reason for overestimation of wind intensity is not clear. However, it has been noted that other mesoscale numerical models have similar problems in sloping complex terrain. Tethered balloon soundings of temperature and wind velocity during smog episodes when the Christchurch Air Pollution Study in 2000 was underway (CAPS2000; Spronken-Smith et al., 2000) demonstrated the existence of a westerly wind above the calm stagnant layer near the surface. It is not clear why the model has a tendency to 'ground' this westerly airflow, but perhaps the rather coarse vertical resolution and/or the difficulty in the prognosis of turbulence intensities in a stably stratified atmosphere contributes to this problem.

Table 2 shows performance statistics for the meteorological component of TAPM. The Index of Agreement (IOA) between modelled and observed data for 1999 is above 0.60 for all of the variables, with relative humidity scoring the lowest value (0.62), and temperature scoring the highest value (0.87) (temperature scoring a higher IOA is a fairly typical result; for example see Hurley et al., 2003). The wind speed, east–west component, and north–south component of wind velocity score 0.66, 0.72, and 0.79, respectively. Although these values suggest the model is performing well, they are still lower than typical examples of simulation by TAPM from other locations (Hurley, 2002; Hurley et al., 2003). We suspect that one of the reasons for this erosion of performance by TAPM in Christchurch is the relatively complex topography of the area. Significant sloping terrain to the west (the Southern Alps) and immediately to the south (the Banks Peninsula), and the fact that TAPM does not handle atmospheric wave activity during strong westerly flow means that simulation of meteorology over Christchurch is more difficult. However, it is important to note that these scores are still very good.

To asses the prediction of PM_{10} concentrations for the entire year, we follow the recommendation of Cox and Tikvart (1990) by looking at the high concentration end of the cumulative frequency distribution and calculating the Robust Highest Concentration ($RHC = C(R) + \left(\overline{C} - C(R)\right) In((3R-1)/2)$, where $C(R)$ is the Rth highest concentration, and $\overline{C}$ is the mean of the top $R-1$ concentrations; this method is

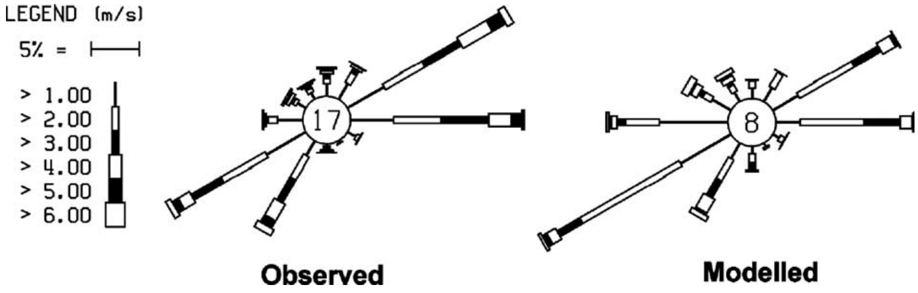

Fig. 4. Wind roses constructed from observed and modelled data from St. Albans monitoring site.

Table 2
Statistics for the TAPM simulation of meteorology over Christchurch for the entire 1999

MEAN_OBS	MEAN_MOD	STD_OBS	STD_MOD	CORR	RMSE	RMSE_S	RMSE_U	IOA	SKILL_E	SKILL_V	SKILL_R
Wind speed (ms^{-1})											
2.6	2.6	1.5	1.6	0.47	1.61	0.8	1.37	0.66	0.93	1.06	1.10
West–East (u) component of wind velocity (ms^{-1})											
−0.4	0.4	2.3	2.4	0.55	2.38	1.32	1.97	0.72	0.85	1.03	1.04
North-South (v) component of wind velocity (ms^{-1})											
0	0.1	1.7	1.7	0.63	1.43	0.66	1.26	0.79	0.75	0.98	0.86
Screen level temperature (°C)											
12.2	11.2	4.3	5.1	0.8	3.29	1.19	3.04	0.87	0.71	1.21	0.77
Relative humidity (%)											
78	65	16.3	19.5	0.45	23.18	15.12	17.27	0.62	1.07	1.2	1.43

Key: OBS: observation; MOD: model predictions; MEAN: arithmetic mean; STD: standard deviation; CORR: Pearson correlation coefficient (0=no correlation, 1=exact correlation); RMSE: root mean square error; RMSE_S: systematic root mean square error; RMSE_U: unsystematic root mean square error; IOA: index of agreement (0=no agreement, 1=exact agreement); SKILL_E=(RMSE_U)/(STD_OBS) (<1 shows skill); SKILL_V=(STD_MOD)/(STD_OBS) (near to 1 shows skill); SKILL_R=(RMSE)/(STD_OBS) (<1 shows skill).

also employed by Hurley et al., 2003). Hannah (1988) suggests a value of 11 for R. The calculated results are illustrated in Fig. 5. The measured annual mean for PM_{10} is 22 μgm^{-3} as opposed to 18 μgm^{-3} calculated by TAPM. This result places a great confidence in the simulated annually-averaged PM_{10} concentrations obtained from other locations over Christchurch where monitoring data are not available, and also indicates that emissions data can produce reliable estimates PM_{10} concentrations. Other skill scores, such as SKILL_E, SKILL_V, and SKILL_R, also show that TAPM can simulate meteorological variables to a satisfactory degree (Table 2).

Fig. 6 illustrates the daily-averaged measured and modelled PM_{10} for January and August. During the summer, there are obviously no home heating emissions and therefore daily averages are very low. Values are usually below 20 μgm^{-3}, with the model frequently underestimating concentrations by about 50%. This is not a great surprise since we have not

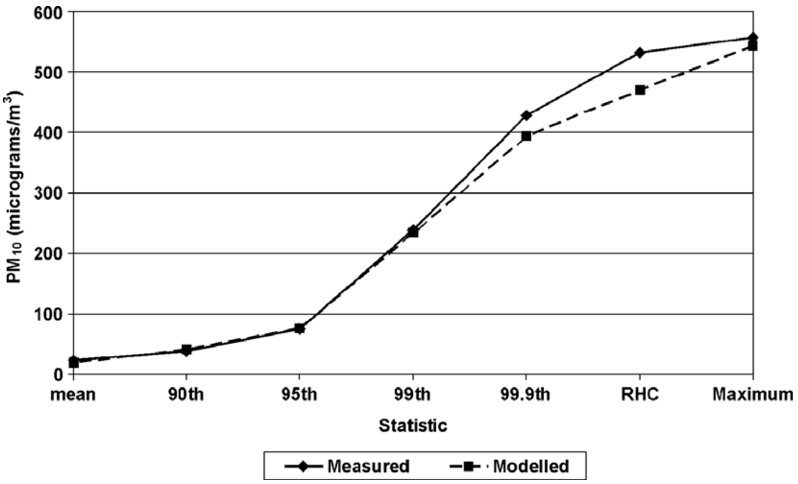

Fig. 5. Statistics for observed and modelled PM_{10} concentrations from the St. Albans monitoring site.

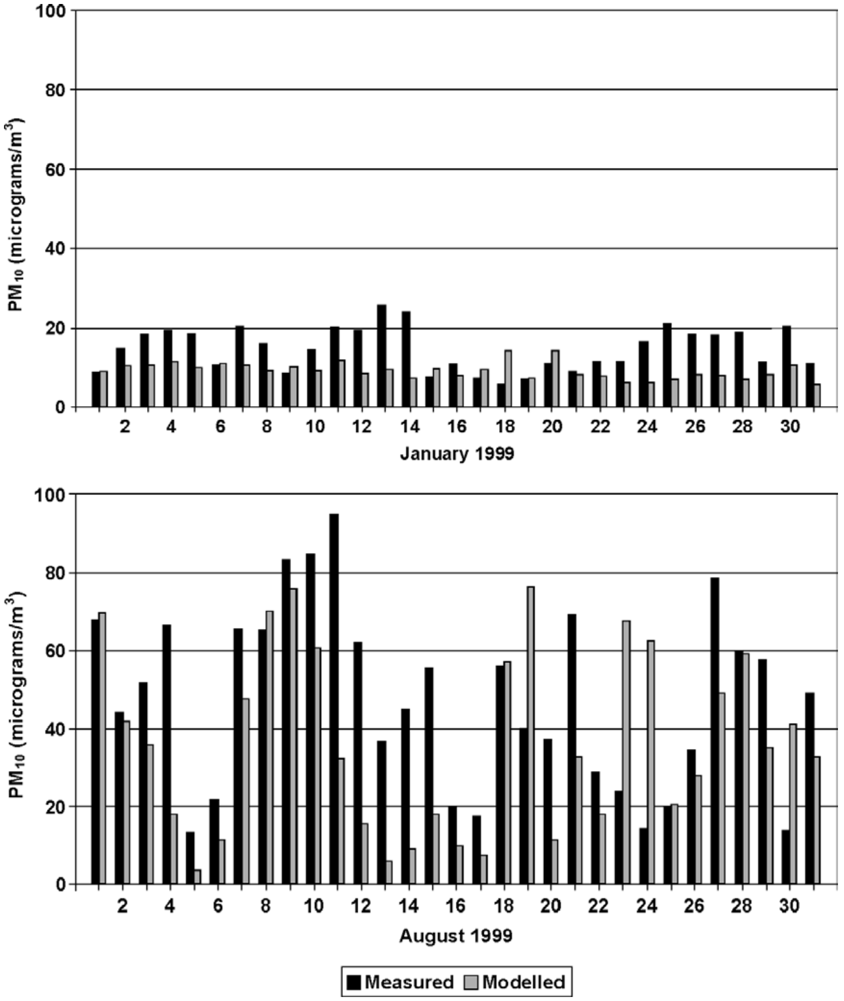

Fig. 6. Daily averaged PM_{10} concentrations-observed and modelled values—for January (top panel), and August (bottom panel) of 1999.

included natural emissions—such as sea salt and other sources of PM_{10}—in the emission inventory. In August, with the cold temperatures and a big contribution from domestic home heating, the daily averages are much higher. The model captures the smog episodes on 7–10 of August, but misses episodes that occur on the 20, 23, and 24. Reasons for this failure are still under investigation (Zawar-Reza et al., 2005), however, as far as annual averages are concerned, we have great confidence in modelled values. Finally, as an example, an exposure map of PM_{10} for the month of July (winter) for each CAU is presented in Fig. 7. Significant variation of PM_{10} concentrations across the CAUs is obvious in this map. These variations reflect the role of meteorology and emissions, and can also be related to social differences in the composition of the resident population (see Pearce et al., accepted for publication).

In summary, we have presented results from a year-long simulation of meteorology and PM_{10} dispersion using TAPM for the city of Christchurch in New Zealand. Compared to other published results using the same model, we find that TAPM's performance in simulating meteorology is eroded somewhat, but not to a degree to affect the skill scores and IOA significantly. The simulated dispersion of PM_{10} is

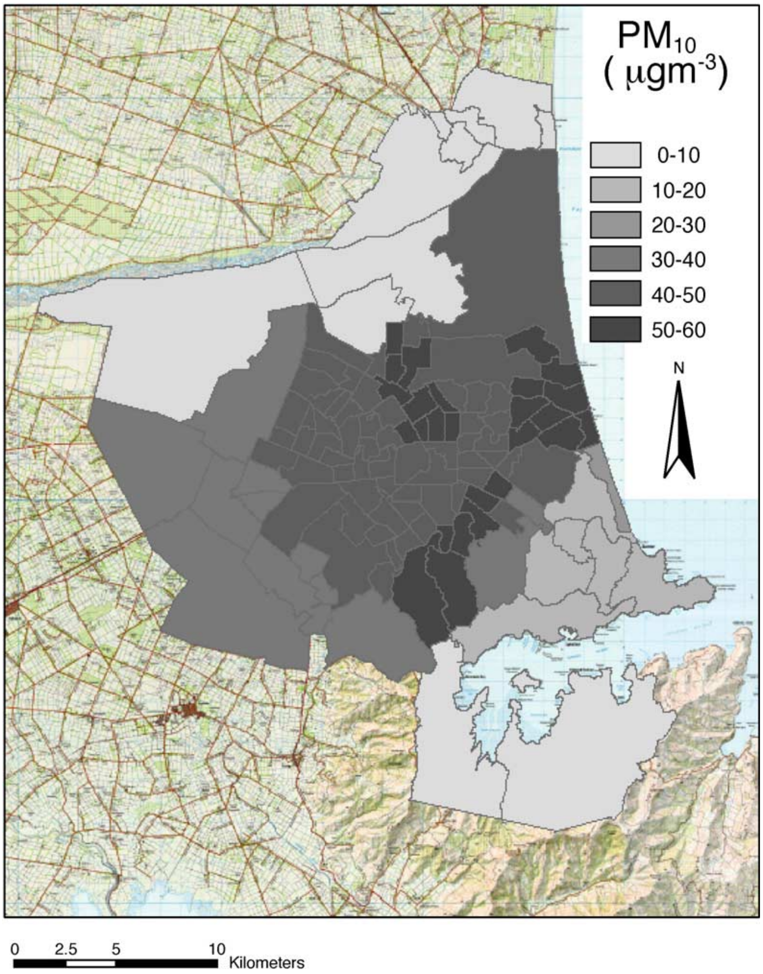

Fig. 7. Mean PM$_{10}$ exposure values for Christchurch Census Area Units for July 1999.

also in good agreement with observed values at a permanent monitoring station. There is only a 4 μgm^{-3} difference in annually averaged concentration of modelled and measured PM$_{10}$.

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