Application of MM5 and CAMx4 to local scale dispersion of particulate matter for the city of Christchurch, New Zealand

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Abstract

A numerical model – Mesoscale model (MM5) – is used in conjunction with the 3-dimensional Eulerian/Lagrangian dispersion model (CAMx4) to model PM_{10} dispersion for a period of 48 hours for the city of Christchurch, New Zealand. In a typical winter, Christchurch usually experiences severe degradation in air quality. The formation of a nocturnal inversion layer during stagnant synoptic conditions, and the emissions of particulate matter (PM_{10}) mainly from solid fuel home heating appliances ('Domestic' factor) leads to severe smog episodes on about 30 nights each winter. The modelling results from the highest resolution computational grid are compared with the observed meteorology and dispersion for winter 2000, when the Christchurch Air Pollution Study (CAPS2000) was underway. Results from a case study in 2003 are also shown. The numerical modelling system is able to simulate surface-layer meteorology and PM_{10} spatial distribution with a good level of skill (i.e. Index of Agreement and Pearson's Correlation Coefficient > 0.8 for PM_{10}).

Keywords: MM5, CAMx4, PM_{10}, air pollution, Christchurch.

1. Introduction

1.1. Physical setting

The city of Christchurch is situated on the coastal edge of the Canterbury Plains in the South Island of New Zealand (Figure 1). The plains slope gently from the Southern Alps to the eastern coast. Banks Peninsula is an eroded volcanic crater that lies on the southern border of the city and reaches a maximum height of 906 m.

The Christchurch urban area covers more than 20,000 hectares of land with an immediate rural fringe of 30,000 hectares. Ninety-seven percent of the population lives in the urban area and the total population is estimated at more than 405,000. Topographically induced local wind systems over Canterbury play an important role in the mesoscale climate of Christchurch.

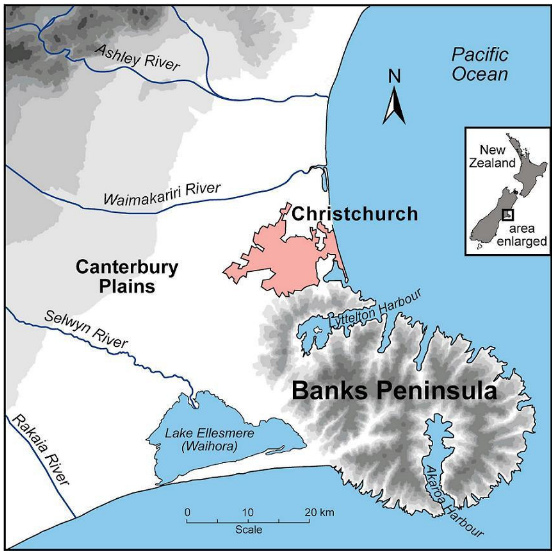

Figure 1 Map of Christchurch region.

Christchurch has a significant wintertime air pollution problem that is dominated by smoke generated by domestic fires burning coal and wood on cold nights (Spronken-Smith et al., 2001). The emissions consist mostly of particulate matter (PM_{10}). After sunset, under anticyclonic weather conditions, a strong surface temperature inversion due to long-wave radiative cooling increases the pollution potential, resulting in high air pollution concentrations. The winter season can be characterized by the frequent occurrence of severe nocturnal smog events, when the health guidelines are exceeded on about 30 nights each winter (Sturman et al., 2001; Aberkane, 2000).

1.2. Local meteorology and air pollution episodes

Previous research into the role of synoptic climatology in pollution episodes has shown that situations with post-frontal southwesterly winds, or with northwesterly winds aloft (but undeveloped at the surface), or with weak easterly synoptic-scale flows are favorable for the development of severe smog events (Owens and Tapper, 1977). The near-surface airflow during smog nights is often dominated by westerly cold air drainage from the Southern Alps, which can enhance the strength of near-surface temperature inversions (Johnston, 2000; Kossmann and Sturman, 2004) and generate zones of stagnant air resulting from convergence with drainage winds down the slopes of Banks Peninsula (Figure 2). The dataset used for validation of the modelling exercise was obtained during The Christchurch Air Pollution Study 2000 (CAPS2000; Kossmann and Sturman, 2004). During CAPS2000, a relatively dense network of automatic weather stations and air pollution measurement stations were setup to more clearly characterize the spatial and temporal heterogeneity of meteorology and pollution dispersion during smog nights.

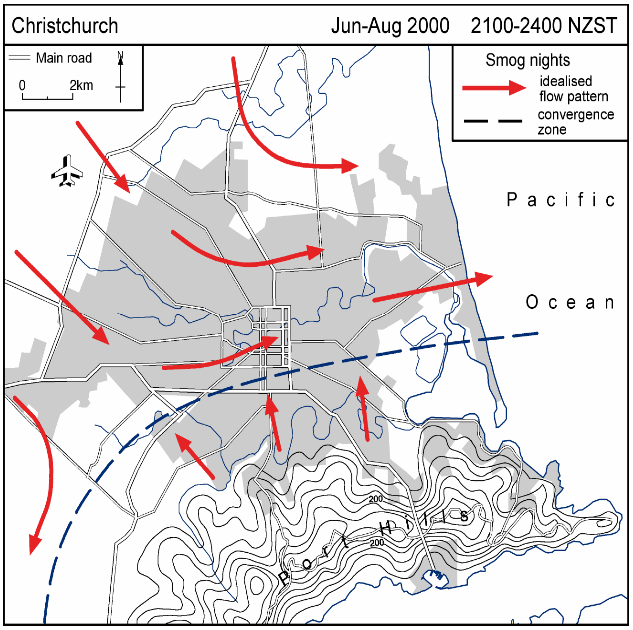

Figure 2 A conceptual model of near-surface airflow during smog episodes over Christchurch.

2. Description of MM5-CAMx4

2.1. Background

MM5 is a non-hydrostatic limited-area mesoscale model using a terrain-following sigma-coordinate system to simulate (predict) mesoscale atmospheric circulations. It was developed by the National Centre for Atmospheric Research (NCAR) (Grell et al., 1994). The Comprehensive Air quality Model (CAMx4) 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 simulates the emission, chemical reactions and removal of pollutants by solving the pollutant continuity equation for each chemical species (ENVIRON, 2003).

The combined MM5-CAMx4 numerical system provides advantages in predicting pollution dispersion over complex terrain, since the mesoscale model calculates surface layer meteorological fields (i.e. vertical profiles of temperature, and turbulence intensities) and then these parameters are used as input to drive CAMx4 to estimate the dispersion of air pollutants.

2.2. Modelling design for MM5

The MM5 simulations shown here used four grids with spatial resolutions of 27 km, 9 km, 3 km and 1 km (Figure 3). The coarsest resolution grid covers nearly all of New Zealand and the 4th grid covers Christchurch and its suburbs (Figure 1 shows the rough geographical extent of grid 4).

The centre of all 4 grids was located at the University of Canterbury in Christchurch (43.318°S, 172.345°W). Topography and land-use distribution was obtained from the United States Geological Survey (USGS) global database (the difference between real orography and the interpolated one for grid 4 was less than a 25% reduction of mean height in the modelled topography).

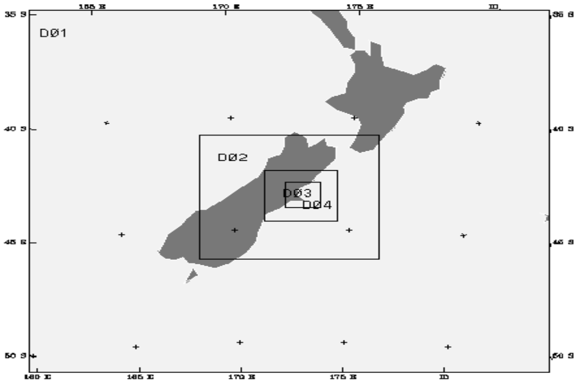

Figure 3 MM5 grid setup.

Global analysis data were used for initialization and nudging of MM5 meteorological fields during each run. To reduce the influence of global analysis on mesoscale features, several methods were used to initialize grid 4, as follows:

- Grid 4 was spawned on the simulation 12 hours into the simulation;
- The first 3 grids were run separately and grid 3 output data were used to evaluate grid 4 (one-way nesting);
- In the first stage, only grid 1 was run with input global analysis data; in the second stage, grids 2 and 3 were initialized by grid 1 output; and in the third stage, grid 4 was run with input data from grid 3.

Based on such typical evaluation statistics as the Index of Agreement (IOA), Pearson correlation coefficient (PCC), and systematic and unsystematic root mean square errors (S-RMSE, U-RMSE), it was found that the last procedure produced the best results.

2.3. Modelling design for CAMx4

The Christchurch gridded emissions data for PM_{10} have a resolution of 1 km and were prepared using GIS (for details see Zawar-Reza et al., 2005). All experiments use the 'Total' emission group option, which is dominated by processes of solid fuel combustion from the 'Domestic', 'Vehicle' and 'Industry' groups (the main contributors to aerosol air pollution: 85–95 %). To account for the diurnal variation in PM_{10} emissions, the Christchurch "mean winter day" emission inventory (Supplied by Environment Canterbury) comes in four time intervals. Each file represents constant in time emissions for the following periods: 10pm – 6am; 6am – 10am; 10am – 4 pm; 4pm – 10 pm. A 5-point time filter was subsequently applied to all initial concentration fields to smooth the difference of emission concentration values between different time periods.

The next step in assimilation of emission fields involved splitting of PM_{10} into the species required for CAMx4. Four main species that make up nearly 100% of PM content were chosen (Ryan, 2002) using the Split Mass Factor (SMF) for each species defined for high pollution nights dominated by wooden smoke These were: Pollutant Elemental Carbon (PEC) with SMF = 0.51; Pollutant Organic Carbon (POA) with SMF = 0.48; Pollutant SO_4 (PSO4) with SMF = 0.0089 and Pollutant NO_3 (PNO3) with SMF = 0.0011.

To calculate PM_{10} dispersion, a 2-level option for vertical layers was chosen (as a comparison, results from 6-level runs are also shown in Figures 6 and 7). The top level in the 2-level mode reaches a height of 40–45 m which typically corresponds to the height of the nocturnal inversion layer where more than 90% of the pollution is trapped (Sturman et al., 2003, pers. comm.).

All simulations with CAMx4 had a spatial resolution of 1 km (coinciding with grid 4 of MM5). To minimize the loss of modeled meteorological information during interpolation of MM5 fields into the CAMx4 grid, CAMx4 was run with the same vertical levels as MM5.

To properly simulate PM_{10} dispersion, CAMx4 usually needs a period of 'spin-up' time. It was found that, generally, the runs that started at midday gave better results (comparison not shown here).

3. Modelling results

3.1. Mesoscale meteorology

Surface radiation balance and partitioning of energy into component fluxes are important drivers of low level airflow. As illustrated in Figure 4, MM5 calculates the net radiation balance very well. The partitioning of net radiation into sensible and latent heat fluxes is also very good (results not shown here), although it is beyond the scope of this paper to describe the turbulence parameterization schemes used with MM5.

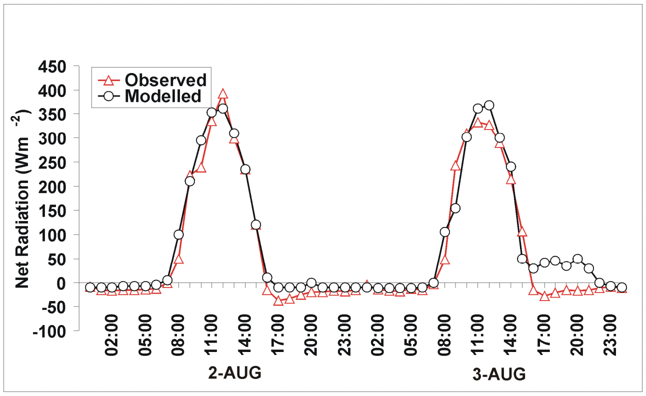

Figure 4 Modeled and measured net radiation flux density.

As shown in Figure 5, MM5 captures the diurnal shift between the daytime north-easterly wind and the nocturnal westerly very well. Index of Agreement (IOA), Pearson correlation coefficient (PCC), systematic and unsystematic root mean square errors (S-RMSE, U-RMSE), as recommended by Wilmott et al. (1985), are represented in Table 1 as a measure of the model's performance. MM5 consistently scored higher than 0.7 for IOA. Values above 0.6 are generally accepted to represent good skill by the model. Therefore, at least for these two days, MM5 performed very well.

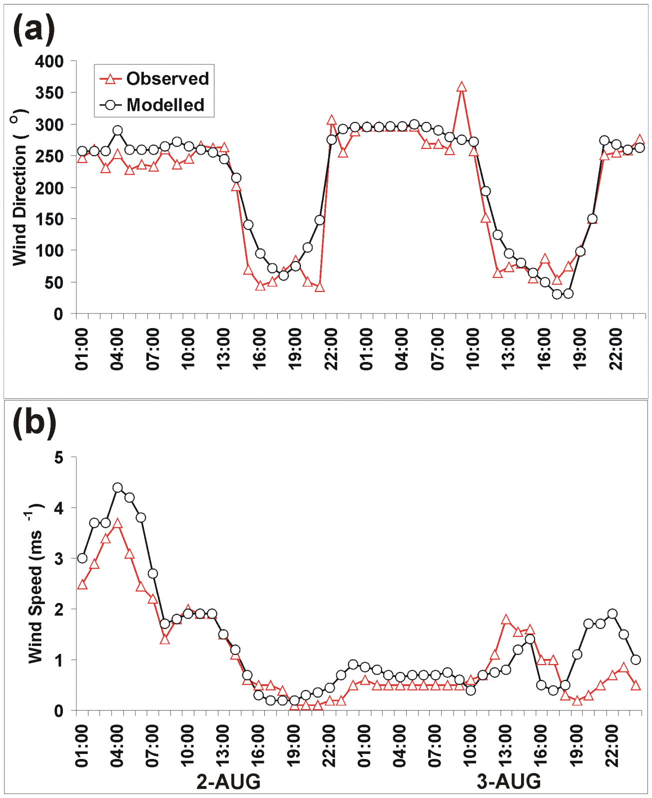

Figure 5 Measured and observed (a) wind direction and (b) wind speed.

Table 1 IOA, PCC, S-RMSE, U-RMSE, 1-6 August 2000.

EXPERMENT	PCC	S-RMSE	U-RMSE	IOA
Wind Speed	**0.71**	0.35	0.81	**0.81**
U-component	**0.85**	0.52	1.16	**0.91**
V-component	**0.71**	0.63	1.06	**0.71**
Temperature	**0.92**	1.14	1.31	**0.80**
Relative Humidity	**0.87**	3.88	5.81	**0.90**

3.2. CAMx4 dispersion results

Time series of observed and modeled PM_{10} (for both 2-level and 6-level CAMx4 runs) are shown in Figure 6 for one of the measuring stations.

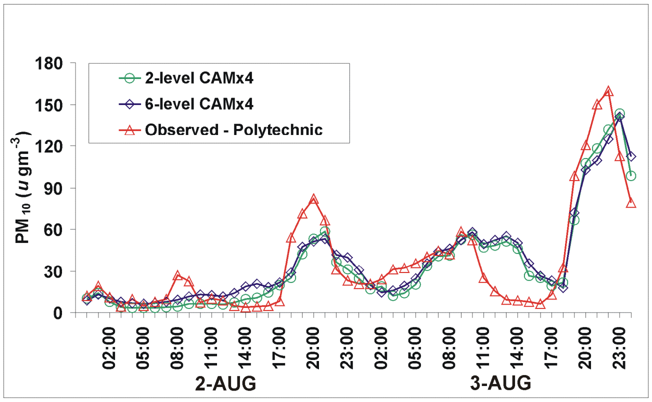

Figure 6 Modelled and measured PM_{10} concentration at Christchurch Polytechnic (south of city centre).

CAMx4 is able to calculate the diurnal variation in ground-level PM_{10} very well. The discrepancy in the results is probably due to the rather coarse temporal resolution of the emission inventory. PCC for modeled and observed PM_{10} concentrations ranged between 0.85 (6-level model) and 0.89 (2-level model), and the IOA was close to 0.91.

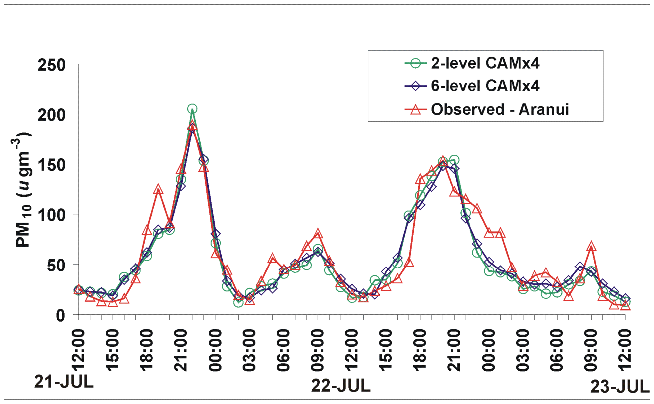

Figure 7 Modelled and measured PM_{10} concentrations at Aranui (northeast of the city centre).

Figure 7 shows additional results from simulations performed for 2003. For this three day period, CAMx4 also performed well. Winter 2003 was colder than winter 2000, with PM_{10} peaks during severe smog nights nearly twice as high as in 2000. Input emission files had to be multiplied by a coefficient of 2.0 to produce realistic modeled results. PCC for modeled and observed PM_{10} concentrations ranged between 0.90 (6-level model) and 0.92 (2-level model), and the IOA was about 0.89 and 0.91.

4. Concluding remarks

This research was undertaken to assess the utility of the MM5-CAMx4 modeling system in predicting PM_{10} concentrations during stagnant synoptic conditions over the complex topography of Christchurch. At least for the case studies shown here, MM5 was able to reproduce mesoscale meteorology to a satisfactory degree, while CAMx4 captured the diurnal variation and the peak concentrations of PM_{10} very well.

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