DISPERSION MODELLING OF PM_{10} FOR CHRISTCHURCH, NEW ZEALAND: AN INTERCOMPARISON BETWEEN MM5 AND TAPM

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Abstract

The performance of two geophysically based high-resolution mesoscale models in simulating the meteorology and dispersion of PM_{10} for the city of Christchurch, New Zealand is assessed. 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 haze episodes about 30 nights each winter. The motivation here is to compare the performance of TAPM against MM5 in the complex topographic setting of Christchurch. A strong incentive for using TAPM as a research tool is its computational efficiency and its ability to perform long-term simulations with relative operational ease.

The modelling results are compared within the context of simulating meteorology and dispersion with a high-resolution computational mesh (grid spacing of 1 km^2) for the period 1-4 August 2000, when the Christchurch Air Pollution Study (CAPS2000) was underway. Initial analysis shows that both models are able to simulate surface-layer meteorology and PM_{10} dispersion with a satisfactory level of skill (i.e. Index Of Agreement > 0.7 for temperature, *u*-, and *v*-components of wind velocity), with MM5 scoring slightly better for all variables.

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

1. Introduction

1.1. Physical setting

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 is 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 (Figure 1). It has a population of 300,000, occupies an area of about 140 km^2, and usually experiences haze 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 (Figure 2).

Due to the paucity of air pollution monitoring sites, investigation of the spatial distribution of PM_{10} during haze episodes has relied heavily on using mesoscale models coupled with air pollution dispersion modules. To this end, verifying modelled dispersion results is important for placing confidence on generated data. We aim to show here that at least during a four day episode in August 2000, The Air Pollution Model (TAPM; Hurley 2002) and Mesoscale Model 5 (MM5; Dudhia 1993) performed a satisfactory calculation of meteorology and the subsequent PM_{10} dispersion over Christchurch.

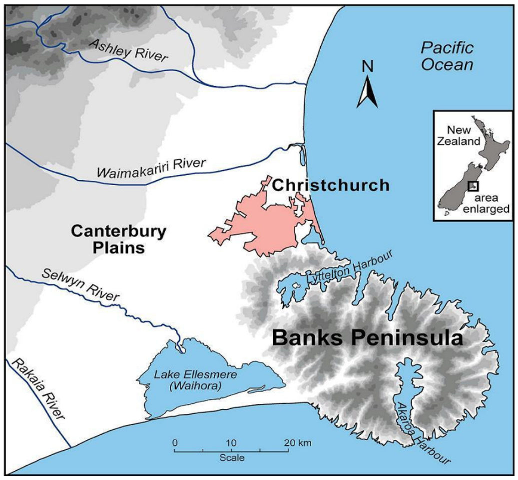

Figure 1. Map of the Christchurch region.

1.2. Meteorology during air pollution episodes

The haze events in Christchurch usually occur during cold and calm nights when atmospheric stability and emissions (mostly from home heating and traffic) are high. A 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 haze events (Owens and Tapper 1977). The near-surface airflow during haze nights is often dominated by westerly cold air drainage from the Southern Alps (Ryan 1975), which can enhance the strength of the surface temperature inversion and generate zones of stagnant air resulting from convergence with drainage winds down the slopes of Banks Peninsula (Figure 2; Kossmann and Sturman 2004).

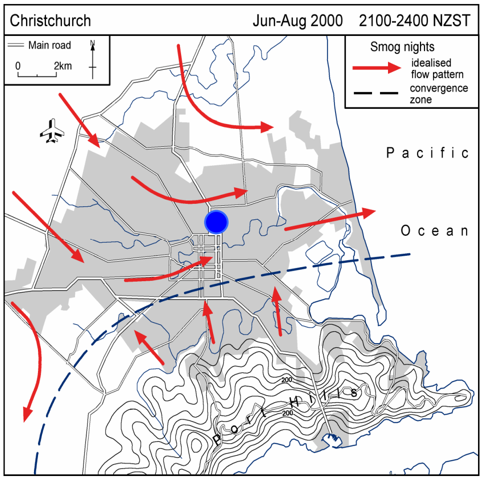

Figure 2. Schematic illustration of the drainage flow pattern over Christchurch during haze nights, 2100-2400 NZST. The location of St. Albans monitoring site is shown by the filled circle (after Kossmann and Sturman 2004).

2. A brief description of MM5 and TAPM setup

Mesoscale models are basically numerical solvers for the equations governing fluid flow. In this respect, any intercomparison exercise has to take into account (and provide information regarding) the boundary conditions (lateral, bottom, and top) and the physics options (including the choice of turbulence closure schemes) employed. It is beyond the scope of this paper to present in-depth information of the choice of modelled parameters – especially for MM5. However, a brief description of how both models treat the surface layer where the observation is taken is given. Both models have parameterizations to distinguish between urban and non-urban surface cover. TAPM sets urban parameters according to Oke (1988) (Table 1). The treatment of surface layer fluxes is described in detail by Hurley (2002). In addition, TAPM adds 30 Wm^{-2} to calculated sensible heat flux values to account for anthropogenic input. Anthropogenic heat flux for Christchurch has been estimated to be only around 6 Wm^{-2}. MM5 provides the option to treat the surface and boundary layer for each grid differently. For the highest resolution grid (grid 4), Chen and Dudhia (2001) Land Surface Model (LSM) scheme is used.

Table 1 Urban Characteristics

	MM5	TAPM
albedo	0.15	0.15
emissivity	0.93	0.95
Roughness (m)	0.5	1

The characteristics of the high-resolution mesh for each model are almost similar in the horizontal but vary in the vertical. The high-resolution mesh for both models had 1 km grid spacing. The authors would like to point out that both models are highly sensitive to the placement of the lateral boundaries of the high-resolution computational mesh. Especially when this boundary is placed over sloping terrain – such as the Southern Alps. Hence, the results shown here were obtained after experimentation with the domain size and placement in order to obtain 'optimal' meteorological fields (i.e. to obtain a physically realistic wind field for example). The geographical extent of the highest resolution grid for both models is roughly the same as the area shown in Figure 1. TAPM is sensitive to the placement of the lateral boundary, especially for the north-east corner of the domain close to the Southern Alps where the topography is steep (the dark grey areas in Figure 1). It is easy to spot numerical ‘noise’ caused by the steep topography as the wind speed seems unusually high. There are many methods to alleviate this problem – including smoothing out the topography, but in this case the lateral boundary is just displaced by a few grid points until the model produces reasonable data. MM5 seems to be more forgiving in this regard.

3. Modelling results

3.1. Surface layer fluxes

Since during settled synoptic conditions surface energetics can be the primary driver of low level airflow, in this section, we will examine calculation of the surface energy balance by both models. All data are extracted from a grid point closest to St. Albans monitoring station (Figure 2). It is very encouraging to see the close agreement of the two modelled net all-wave flux density calculations (Figure 3). MM5 tends to just slightly calculate higher values than TAPM. Although surface fluxes are an important ingredient for climate analysis, regular measurement of these components are rarely available. During Christchurch Air Pollution Study (CAPS2000; Spronken-Smith *et al.* 2002) flux measurements using eddy covariance methods were obtained for the month of July only, and unfortunately data are not available for 1-4 of August. However, according to Spronken-Smith *et al.* (2004), net-all wave values ranged between 200 to 300 Wm^{-2} during the day in July. Both MM5 and TAPM calculate comparable values to the measured net all-wave flux density.

TAPM subsequently tends to overestimate sensible heat flux density by about 80 Wm^{-2} on all four days (Figure 3); partially due to the overestimation of the anthropogenic component (see previous section). Spronken-Smith *et al.* (2004) report daytime values ranging between 50 to 100 Wm^{-2}, so that MM5 calculations seem to be more inline with actual values. However, latent heat flux densities are generally in agreement between the two models. These are also comparable with values measured by Spronken-Smith *et al.* (2004).

It is not clear why TAPM overestimates the day time sensible heat flux. Perhaps TAPM does not partition an adequate amount of the net radiation flux into the ground. This point has to be investigated further.

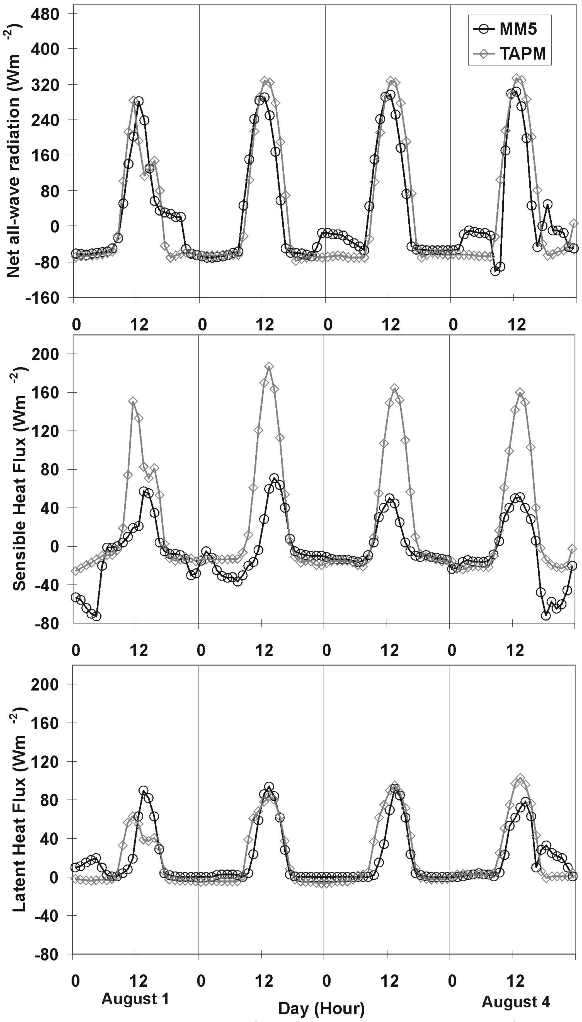

Figure 3. Time series of modelled components of the surface energy balance. Net all-wave (top), sensible heat flux (middle), and latent heat flux (bottom).

3.2. Meteorology

Examination of the performance of the dynamic core for both models is performed through validation of predicted wind speed and direction at a point. Figure 4 illustrates measured and modelled data for the St. Albans location. Both MM5 and TAPM have been able to capture the diurnal shift from the night time westerly flow to day time easterly flow for each of the four days. However, the duration of flow in each phase has been simulated differently. Comparison of wind speeds shows that TAPM has more difficulty in predicting the nocturnal stagnant wind speeds around mid-night on August 2nd and 3rd (Figure 4). The reason for this is not clear, yet MM5 performs better in this regard and manages to capture the stagnant conditions.

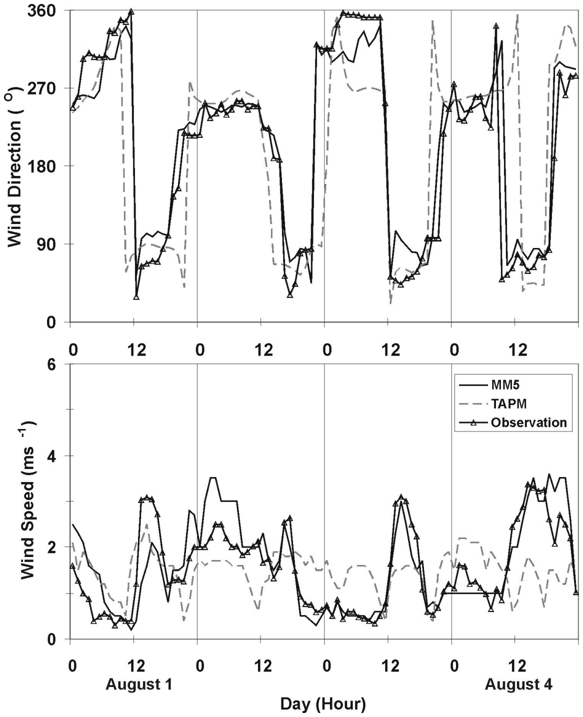

Figure 4. Time series of observed and modelled wind direction (top) and wind speed (bottom) at St. Albans monitoring station.

Evolution of calculated surface temperature usually provides a good assessment of how the models dynamic core performs. TAPM cools low level air excessively early in the morning on 2nd of August, whereas it doesn't sufficiently cool the air on 3rd of August. However, both models perform well during the crucial window when PM_{10} concentrations build up (5 to 11 pm).

In addition, validation of predicted (P) modelled data against observation (O) was done through statistical performance measures. These include root mean square error (RMSE) $=[\overline{(P-O)}]^{1/2}$, and index of agreement (IOA) $=1-[\overline{(P-O)^2}/\overline{(|P-\overline{O}|+|O-\overline{O}|)^2}]$ based on the recommendation of 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. Table 1 presents IOA scores for both models and shows that MM5 tends to score higher in all variables. This is especially true for the wind speed, where TAPM systematically tends to overestimate nocturnal values.

Table 2 Index of Agreement scores.

	MM5	TAPM
Wind Speed	0.91	0.71
***u*-component**	0.87	0.70
***v*-component**	0.84	0.79
Temperature	0.96	0.93

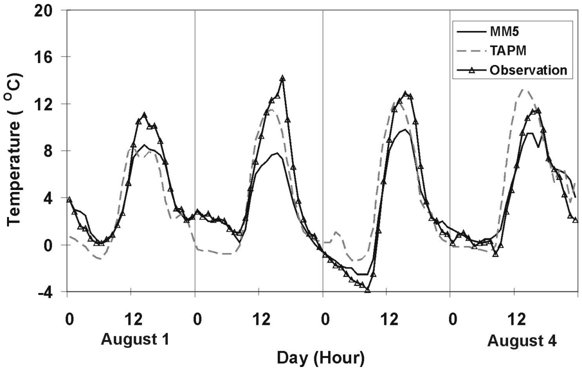

Figure 5. Time series of observed and modelled screen-level temperature at St. Albans monitoring station.

3.3. PM_{10} dispersion results

The only method of verification used here for assessing the prediction of ground level concentration of PM_{10} is comparison with measurements taken by Environment Canterbury's St. Albans monitoring site (Figure 6).

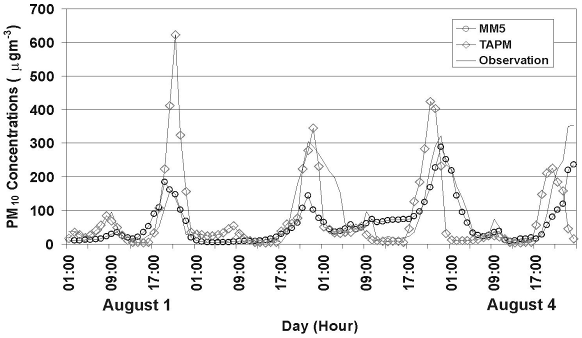

Figure 6. Comparison of observed PM_{10} concentrations against modelled at St. Albans monitoring station.

Keeping in mind the fact that the emission inventory for Christchurch does not have a high temporal and spatial resolution, there is no clear indication of which model performs better. TAPM grossly overestimated peak concentrations for 1st of August, although it estimates the peak concentration better on 2nd of August.

It is beyond the scope of this paper to examine the underlying reasons for discrepancies. A thorough study of the way both models calculate the evolution of the vertical structure of the atmosphere has to be undertaken. However, two points have to be born in mind; the first is that numerical models and their associated air pollution modules are only an *approximation* to nature, and second, the modelled values are representative for a *grid volume*, whereas measurement are representative for a *point* only.

Dispersion of air pollution is, of course, a three dimensional problem, even under strong inversion conditions. Therefore, it might be instructive to test how TAPM and MM5 predicted vertical profiles of meteorological variables. Figure 7 has been included for this purpose. The decision to plot data for 2100 NZST on August 2nd was arbitrary, and it just happens that TAPM calculated a better prediction for all three profiles. Indeed as can be seen from Figure 6, MM5 underestimated PM_{10} concentrations on this night. TAPM captures the vertical structure of potential temperature, and wind speed and direction very well, in comparison to the poor prediction by MM5. The wind shear that is predicted by MM5 at 200 m AGL is absent from both TAPM and observations.

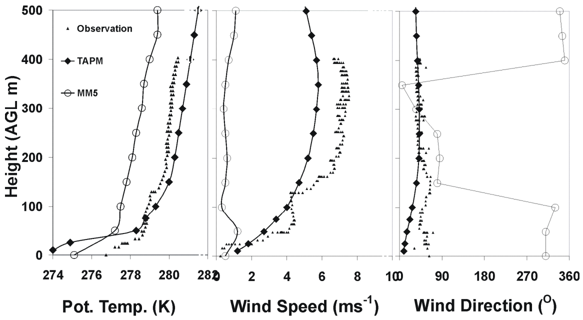

Figure 7. Comparison of vertical profiles of potential temperature (left), wind speed (centre), and wind direction (right) at the University of Canterbury.

MM5 is able to do a better job of calculating vertical profiles on the other nights (results not shown here).

4. Concluding remarks

Research is underway to examine the ability of two different mesoscale models to predict PM_{10} dispersion over the city of Christchurch during haze episodes. We have presented modelled calculations of basic parameters – such as the surface fluxes, wind speed, and wind direction – against measured data for a four day period in August 2000. Initial assessment of modelled data suggests that both MM5 and TAPM can predict meteorology and dispersion satisfactorily for this episode, however MM5 scores higher in all categories, especially for wind speed..

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