Application of MM5 to study of air pollution in Christchurch, New Zealand – some problems of using MM5 with global analysis data

Mikhail Titov, Andrew P. Sturman and Peyman Zawar-Reza

Centre for Atmospheric Research, University of Canterbury, Christchurch, New Zealand,
mti18@student.canterbury.ac.nz

ABSTRACT

The MM5 mesoscale model is used to model near-surface meteorology for research into the dispersion of PM over time periods from 24 to 72 hours for the city of Christchurch, New Zealand during winter, when severe degradation of air quality is experienced. The formation of a strong nocturnal inversion layer during stagnant synoptic conditions and local breeze circulations are the typical meteorological conditions for high concentrations of particulate matter (PM) in the near-surface boundary layer, resulting in severe smog episodes on about 30 nights each winter. The modelling results from the highest resolution 4th grid are strongly dependent not only on MM5 dynamical–physical parameterisation, but also on the method of global data analysis assimilation. The output meteorology resulting from different schemes of global data assimilation by MM5 is compared with observations from winter 2000, when the Christchurch Air Pollution Study (CAPS2000) was undertaken. MM5 is able to simulate surface-layer meteorology with a good level of skill, but the problem of the use of global analysis data as a potential source of type 1 and type 2 errors is quite serious for the calculation of PM concentrations. Following an upgrade of available computer resources, the WRF model (utilized) will be used to investigate possible ways of dealing with this problem on a more precise numerical level.

Key Words: MM5, CAPS2000, error type, PM, Christchurch area, WRF.

INTRODUCTION

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, while 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 400,000. Topographically induced local wind systems over Canterbury play an important role in the mesoscale climate of Christchurch.

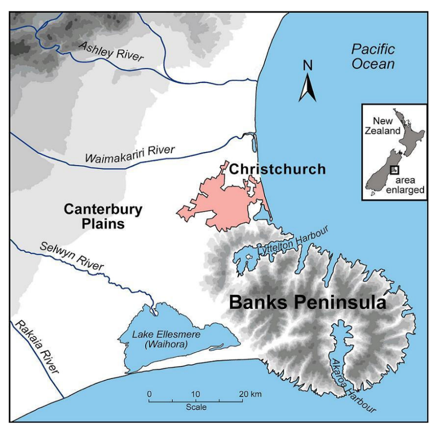


Figure 1 Map of the Christchurch region.

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} and $PM_{2.5}$). 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).

Local meteorological and global analysis data used to model air pollution episodes

Previous research into 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 favourable 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 this major field campaign meteorological data were collected from a network of 7 existing and 8 additional automatic weather stations (Kossmann and Sturman, 2002) within the city, as well as from two instrumented towers, measuring radiation balance, temperature, relative humidity, wind speed and wind direction. Continuous vertical profiles of wind and atmospheric stability were obtained from a SODAR. The observation programme ran from June to August with an intensive period during the months of July and August, when several special observation periods were undertaken. These involved measurements of vertical profiles of the atmosphere using radiosondes and tethered balloons.

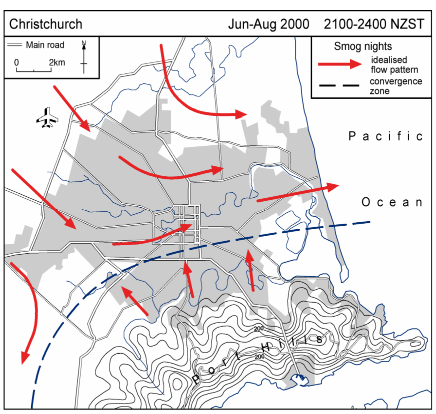


Figure 2 A conceptual model of near-surface airflow during smog episodes over Christchurch (from Kossmann and Sturman, 2004).

Input data from global analyses in regular horizontal and vertical grids provide essential information for the evaluation of MM5, and the finer the resolution of input data the better the possibilities to utilize and adjust MM5 for fine scale reproduction of the air circulation over the Christchurch area. In our case, the vertical resolution of input data plays as important a role as horizontal resolution because baroclinic factors play a very significant role in the complex topographic influence on mesoscale air circulation (Sorteberg *et al.,* 2001). Global analysis data of the NCEP Global Tropospheric Analysis (NCEP GTA) were used. The full description of the data (ds083.2) is: collected 6-hourly, with 1 x 1 degree global coverage resolution, derived from the FNL (final) run of the global data assimilation model. This includes use of additional observations that have been collected through at least six hours after the synoptic time, making the data potentially more accurate and therefore more suitable for our research. On the other hand, the difference of spatial scales between global analysis meteorology (at the synoptic scale) and air circulation over Christchurch (at the local scale) initially creates a conflict between input data from the global analysis and the accuracy of local circulation representation evaluation of MM5.

Modelling design for MM5

The MM5 simulations shown here were run using four grids (3 nested ones) with spatial resolutions of 27 km, 9 km, 3 km and 1 km (Figure 3), 37 – 43 vertical levels with σ range 0.999 (bottom) - 0.010 (top - deep atmosphere) and 12 - 14 levels in the lowest 500 metres. The coarsest resolution grid covers nearly all of New Zealand and the 4th grid covers Christchurch and its suburbs. 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).

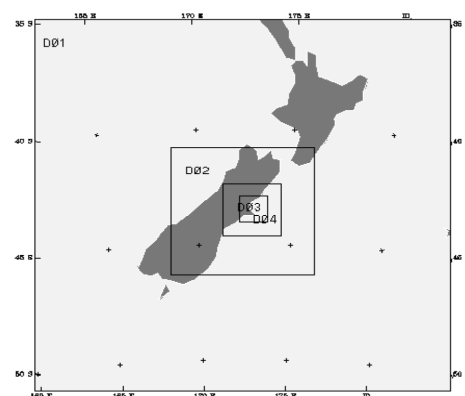


Figure 3 MM5 grid setup.

The mixed-phase explicit moisture scheme, Grell cumulus parameterisation, MRF (Medium Range Forecast model) and Blackadar planetary boundary layer models, rapid radiative transform method, and five-layer soil model with bucket soil moisture scheme were used as physical options of MM5V3.5.3 and MM5V3.6.1 (Dudhia, 2002).
Evaluation statistics, such as Index of Agreement (IOA), Pearson correlation coefficient (PCC), systematic and unsystematic root mean square errors (S-RMSE, U-RMSE), were applied.

MODELLING RESULTS

Different methods of grid 4 initialization

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

- Grid 4 was spawned on the simulation 24 hours later (warm-up time and 2-way interaction during the run of all 4 grids) – experiment 4x1;
- The first 3 grids were run first and grid 3 output data were used to initialise grid 4 (one-way interaction) – experiment 4x2;
- In a three stage process, only grid 1 was run with input from global analysis data; after which, grids 2 and 3 were initialized by grid 1 output; and finally, grid 4 was initialised with input data from grid 3 – experiment 4x3.

Every method was run 4 times over 48 hours for grid 4 with different input-nudging meteorology over time interval 17 July - 6 August 2000.

In the first series of experiments, grid 4 started 24 hours later than the first 3 grids and was run for 48 hours (total time of a run was 72 hours). In experiment 4x1 the first three grids started at 1200 UTC on 31 July 2000 and the fourth grid started 24 hours later at 1200 UTC on 1 August 2000, and all grids finished at 1200 UTC on 3 August 2000. The wind fields presented in Figure 4 result from the MM5 run for grid 4 at two time points and show daytime easterly–northeasterly winds over the Christchurch area (the daytime breeze circulation – Figure 4a) and obvious westerly–southwesterly near-surface winds (the nocturnal breeze and drainage circulation – Figure 4b).

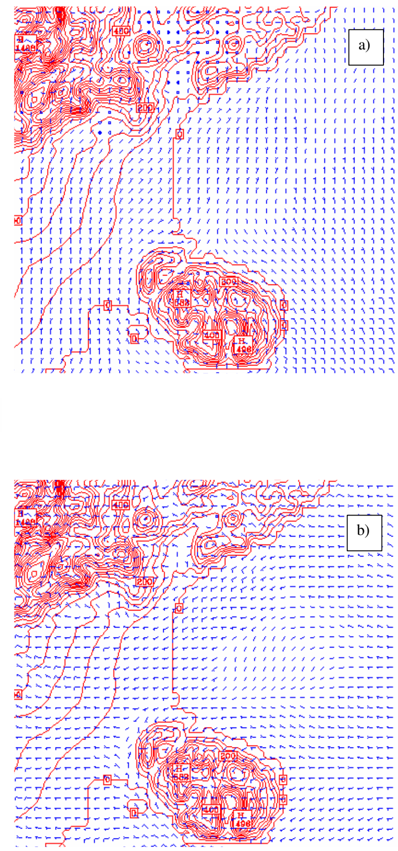


Figure 4 Spatial distribution of MM5 modelled near-surface wind for experiment 4x1, grid 4, σ=0.999 (h = 7 m): a) 1700 NZST on 4 August 2000 (41 hour forecast); b) 0000 NZST on 5 August 2000 (48 hour forecast).

The second series of experiments (4x2) consisted of 2 stages: in the first stage, the first 3 grids were run with exactly the same parameterisation and configuration that had been used in the previous experiment. The output information for grid 3 was dumped hourly and was interpolated as input and used as hourly nudging data to run grid 4 over 48 hours. Therefore, initially 3 grids were initialised simultaneously with two-way interaction and during the second stage only the 4th grid was computed with a condition of relaxation and with input data from grid 3 output. Figure 5 shows wind fields for grid 4 from MM5 for the same two time points during the 4x2 experiment, showing a daytime onshore breeze over Christchurch (Figure 5a) and with nocturnal westerly drainage winds (Figure 5b).

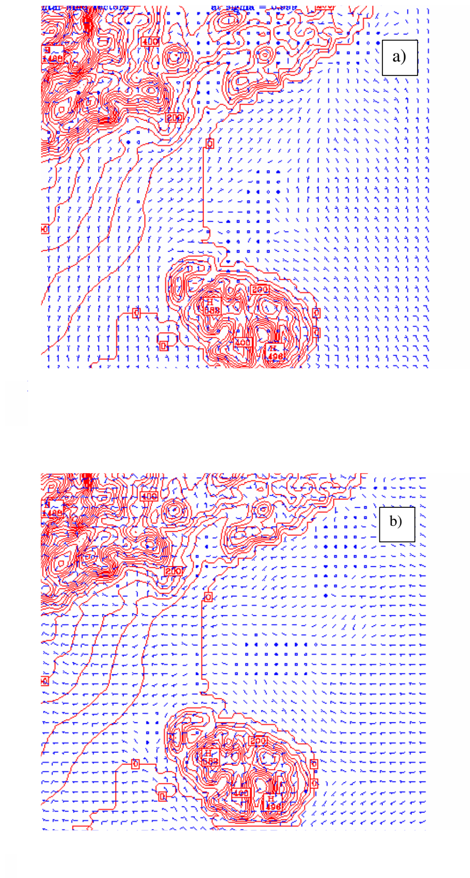


Figure 5 Spatial distribution of MM5 modelled near-surface wind for experiment 4x2, grid 4, σ=0.999 (h = 7 m): a) 1700 NZST on 4 August 2000 (41 hour forecast); b) 0000 NZST on 5 August 2000 (48 hour forecast).

In the third series, initially only grid 1 was run with input data from the global analysis; the grids 2 and 3 were initialized using grid 1 output; and finally, grid 4 was initialised using input data from grid 3. Figure 6 shows wind fields for grid 4 of MM5 for two time points for the 4x3 experiment, showing daytime stagnation over Christchurch (Figure 6a), and with nocturnal drainage winds (Figure 6b).

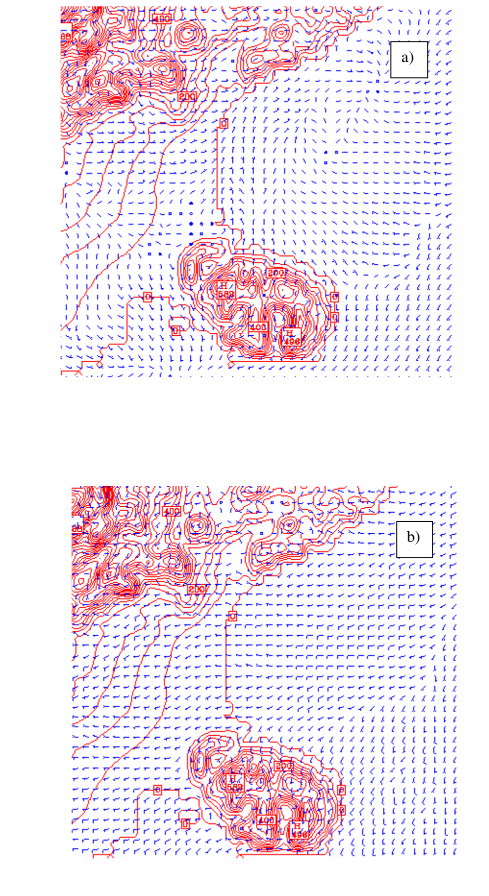


Figure 6 Spatial distribution of MM5 modelled near-surface wind for experiment 4x3, grid 4, σ= 0.999 (h = 7 m): a) 1700 NZST on 4 August 2000 (41 hour forecast); b) 00000 NZST on 5 August 2000 (48 hour forecast).

Comparison of modelled near-surface fields of wind, temperature and relative humidity with observed data from CAPS2000 measurement sites for the Christchurch area was undertaken for grid 4 over the time period 1–7 August 2000. All the observations shown in Table 1 were obtained from 12 surface observation sites that were operated during CAPS200.

Table 1 Index of Agreement (IOA), Pearson's correlation coefficient (PCC), systematic & unsystematic root mean square error (S-RMSE & U-RMSE) for 1-7 August 2000 for experiments 4x1, 4x2, 4x3.

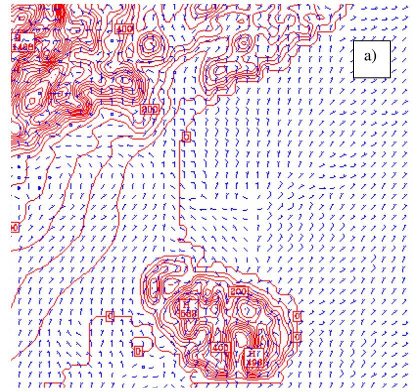
EXPERMENT	PCC	S-RMSE	U-RMSE	IOA
Wind Speed (m/s)				
Experiments 4x1	0.70	0.36	0.90	0.82
Experiments 4x2	0.65	0.28	0.71	0.75
Experiments 4x3	0.77	0.17	0.51	0.87
U-component (m/s)				
Experiments 4x1	0.69	0.85	1.46	0.80
Experiments 4x2	0.79	0.53	0.96	0.86
Experiments 4x3	0.91	0.23	0.61	0.95
V-component (m/s)				
Experiments 4x1	0.54	0.85	0.92	0.60
Experiments 4x2	0.53	0.73	0.76	0.65
Experiments 4x3	0.59	0.37	0.49	0.76
Temperature (°C)				
Experiments 4x1	0.92	1.49	1.52	0.88
Experiments 4x2	0.91	2.04	1.23	0.90
Experiments 4x3	0.94	1.37	1.90	0.90
Relative Humidity (%)				
Experiments 4x1	0.67	6.47	9.56	0.81
Experiments 4x2	0.86	7.10	6.68	0.89
Experiments 4x3	0.87	5.41	5.82	0.91

It should also be noted that although the procedure adopted in experiments 4x3 seems to be very complex, the accumulated CPU time for all experiments is approximately the same.

Case study days and error analysis

Air circulation in the boundary layer over Christchurch is the result of interaction of the prevailing synoptic scale flow assimilated by the model from input files of global analysis data and the mesoscale circulation created during MM5 runs by local factors in the Christchurch area. The effect of the using global analysis data on overestimation of the intensity of synoptic scale processes and the suppression of local air circulation over Christchurch during MM5 runs creates a type I error, because the null hypothesis (heavy smog) is rejected in the research with a high level of reliability (generated by dominant strong air flow) when a heavy smog night is observed. The rejection of a heavy smog night when it is true could lead to serious health problems in Christchurch and its vicinity in case of the pollution forecast, which is not the case for overprediction of aerosol pollution (the type II error).

Two experiments were run for the time period 22–24 July 2000. This period was affected by strong southwesterly winds (global analysis data) and by heavy pollution at night between 23 and 24 July 2000 (observations), implying stagnant near-surface airflow with local circulation dominating. Modelling schemes 4x1 and 4x3 were applied and the results are shown on Figure 7 for the 3-stage method (scheme 4x3 - 7a) and for the 1-stage method (scheme 4x1 – 7b) for daytime breeze.



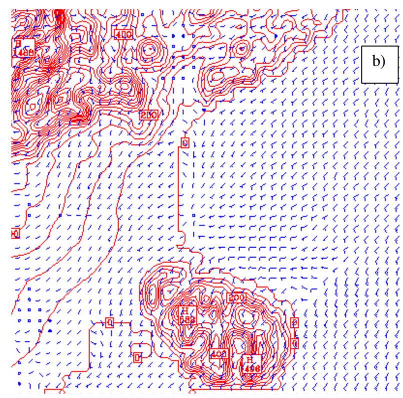


Figure 7 Spatial distribution of MM5 modelled near-surface wind, grid 4, σ=0.999 (h = 7 m): a) scheme 4x3, 1400 NZST on 23 July 2000; b) scheme 4x1, 1400 NZST on 23 July 2000 (14 hour forecast).

The experiment provides evidence of the development of two different scales of process (synoptic scale circulation and local orographically induced airflow) and illustrates once again the real danger of producing type I errors using global analysis input data (i.e. rejection of a high smog hazard forecast when a heavy pollution night actually occurs).

Problems of WRF utilization via MM5 utilization

All our MM5 calculations were produced on a Sun workstation (UltraSpark) connected to computer system with specification equivalent to Pentium 5. A 48-hour MM5 run using model parameters described above usually took about 200 – 250 hours of CPU time depending of the vertical resolution of the precise experiment. Installation of the WRF code created no serious problems during test run the model for several ideal cases of the air flow over 2- and 3-dimensional obstacles.

An attempt to run a real case with 3 grids (2 nested ones) from a "test" dataset at 24 hours (12:11-06-2001 – 12:12-06-2001) was successful, but took about 250 hours of CPU time (more than 10 hours per 1 model hour). Such a big computer time is considered to be a result of technological development: MM5 was created in the era of the first super-computers (early 80) with relatively slow calculation speed, and all programs were optimized to save CPU time. The WRF model was developed on modern super-computers, required multi-parallel processor machines. The increased CPU time wasted by our Sun station to run WRF, fostered us to buy a new multi-parallel computer (this idea is now in process of realisation) that definitely would move MM5 – WRF application on a new level including possibility of short-time weather forecast for the Canterbury area of New Zealand.

CONCLUSION

This research was undertaken to show the possibilities of using MM5 in the South Island of New Zealand to reproduce air circulation for the Christchurch area (during winter time) with input data from the global analysis, and to investigate an expected conflict between synoptic scale processes imported by the global analysis and local scale processes over Christchurch for MM5 evaluation. The initial problems of MM5 substitution by WRF meteorological model are also examined.

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