Prognostic urban-scale air pollution modelling in Australia and New Zealand – A review

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ABSTRACT

This paper reviews research conducted in the past two decades in urban-scale air quality modelling in Australia and New Zealand, with emphasis on prognostic models. With advances in computer technology – especially desktop computers – air pollution dispersion modelling is now a feasible undertaking not only for well-funded research institutions, but also for air quality consultants. It has been suggested that as prognostic models become more user friendly they will eventually replace Gaussian dispersion models as a tool for urban air quality impact assessment. However, for now, Gaussian models are still widely used. Prognostic dispersion models have been applied to a number of Australian and New Zealand urban regions with relative success. In Australia, the major focus has been in simulating photochemical smog episodes. In contrast, New Zealand studies have mostly dealt with nocturnal dispersion of particulate matter during stagnant weather conditions.

INTRODUCTION TO ATMOSPHERIC SIMULATION MODELLING

Due to unprecedented advances in computer technology during the past two decades, simulation of physical processes in the environment is becoming more feasible. Computer simulations are employed as tools to study and solve environmental issues and problems. A simulation attempts to roughly duplicate (approximate) the behaviour of a physical system, such as the atmosphere, using mathematical relationships describing the laws of physics (Wright and Baker, 2002; Pielke, 2002). In fact, the science of weather forecasting and the need to simulate weather into the future was a major force behind the development of 'supercomputers' in the 1960s. Air pollution climatology is a field that relies extensively on computer modelling. Currently, numerous models are available that simulate air pollution chemistry, dispersion and transport, with varying degrees of sophistication.

Air pollution dispersion modelling

Modelling air pollution dispersion at an urban-scale has traditionally and most commonly been achieved using two approaches (urban-scale or local-scale have spatial dimensions from tens of metres to tens of kilometres). The first approach is based on the Gaussian diffusion theory, which is applied to dispersion in the atmosphere (Arya, 1999). The primary use of Gaussian models is in determination of near-source (short-range) maximum ground-level concentration (GLC). Their appeal originates from their conceptual simplicity, cheap computational requirements, and the official 'blessed' status given to them by regulatory agencies (US Environmental Protection Agency, 1986). The second approach – which is the focus of this paper – is physically more comprehensive, and aims to simulate the motion and turbulence characteristics of atmospheric behaviour by solving the detailed set of mathematical relationships describing fluid flow. These relationships are commonly referred to as the primitive equations. Models based on these equations can simulate a spectrum of meteorological phenomena ranging from classical thermally generated winds like sea-breezes to dynamically complex systems such as hurricanes. In air pollution climatology, however, there is no need to simulate weather associated with unsettled conditions since pollutant concentrations do not reach high levels.

The following provides a review of urban-scale air quality modelling research conducted in Australia and New Zealand using the latter approach. The modelling is based on two interacting components that were developed separately and first brought together to simulate the formation of photochemical smog (Scheffe and Morris, 1993). The first component – the meteorology module – predicts meteorological variables such as wind speed, wind direction, temperature and turbulence intensity. There are commonly two methods applied here. The prognostic method (or dynamic method) retains the time dependent variables in the primitive equations which allows for determination of temporal and spatial variation in meteorological variables. With the diagnostic approach, the time-dependent variables are removed; therefore the meteorological field is determined (diagnosed) by interpolation of observed data. Simply put, a prognostic model has forecasting capabilities, in contrast to a diagnostic model which requires extensive observational data to reproduce meteorological fields. It is beyond the scope of this paper to expand this topic further, but interested readers are referred to Pielke (2002) and Godfrey (2002). Those interested in a more in-depth treatment of the meteorological component of models – including derivation of the primitive equations and the numerical methods used to solve them – should refer to Pielke (2002), Garratt (1994) and Stull (1998). The second component of air quality models – the pollution module – addresses the chemical transformations of the pollutants that occur as they are transported by the mean wind and diffused by atmospheric turbulence. Atmospheric chemistry is a complex science, and the number of chemical reactions to consider is daunting. See Sillman (1999) for a review of the literature on urban photochemistry. Jacobson (2000) also provides a comprehensive reference that describes computational techniques used to simulate atmospheric chemistry.

It should be pointed out that prognostic models discussed here do not attempt to explicitly simulate micro-scale (street canyon scale) meteorology and dispersion. One reason is that for computational purposes, it is highly impractical to run the models at a high enough spatial resolution to resolve street canyons (even if the coordinate system employed by the model allowed such calculation). Therefore, in general, prognostic models treat the effects of urban canopy on meteorology and turbulence in a statistical sense by using, for example, the well known Monin-Obukhov similarity theory.

Modelling applications

Successful use of models requires site-specific knowledge regarding (1) the physical processes responsible for atmospheric dispersion, (2) temporal and spatial variability of pollutant emissions, and (3) pollutant transformation and deposition processes. The results acquired from air quality modelling are generally used to assess the air quality impacts due to accidental and/or routine pollutant emissions from site-specific sources. However, the model predictions may also be used to:

- acquire additional insight into the physical and chemical processes responsible for pollutant dispersion and transformation;
- assess the complex problem of emission reduction strategies;
- provide fallout information of hazardous substances in case of accidental release

– radiological, chemical or biological;
- fill in the gaps between air pollution monitoring sites, as systematic monitoring is costly; and
- map exposure and predict spatial variability in the health effects of air pollution.

URBAN-SCALE MODELLING IN AUSTRALIA

Brief background

Australia's major metropolitan areas are situated along its vast coastal plains and experience degradation in air quality due to photochemical smog (Physick, 1996; Ma Yimin and Lyons, 2000, 2003). Poor air quality episodes are frequently associated with thermally driven wind systems such as sea/land breezes. Hence, the recirculation over the source area of pollutants emitted during the previous day(s), is an important contributing factor to the accumulation of air pollution (Physick, 1996).

Modelling approaches

One of the research models in common use in the 1980s was the Colorado State University Mesoscale Model (CSUMM; Mahrer and Pielke, 1977; McNider and Pielke, 1981). This model was used by Australian researchers to increase their understanding of the physical processes affecting pollutant dispersion over their coastal and complex terrain environments, such as the Victorian power generation region of the Latrobe Valley (Abbs and Physick, 1992; Physick and Abbs, 1991). In particular, the Lagrangian Particle Model component of the CSUMM model was further developed and adapted to simulate nocturnal inversion break-up, fumigation and dispersion in the convective boundary layer (Hurley and Physick, 1990, 1991, 1993a, 1993b). The CSUMM model was also used to provide wind and turbulence fields needed to drive the California Institute of Technology (CIT) photochemical model (Harley *et al*., 1993), in order to examine urban meteorology and dispersion on high ozone days in Melbourne and Perth (Cope *et al*., 1990; Cope and Hess, 1998).

During the early 1990s, the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) regional-scale meteorological model (DARLAM – see Kowalczyk and McGregor, 2000) was modified to urban-scale meteorological simulations. It was subsequently coupled with CSIRO's modified version of the CSUMM Lagrangian Particle Model to produce the Lagrangian Particle Dispersion Model (LADM – Physick *et al*., 1994; Physick and Hurley, 1994, Hurley, 1994). This model was applied to numerous studies of worst-case air quality episodes for a number of industrial and urban regions in Australia and overseas (e.g. Hunter Valley and Central Coast of New South Wales – Physick *et al*., 1992; the Gladstone industrial region of Queensland – Physick *et al*., 1995; and Perth and Sydney urban meteorology conducive to high ozone days – Hurley and Manins, 1995; Hurley *et al*., 1996a, 1996b).

More recently, two new prognostic air pollution modelling capabilities have been developed in Australia. One is the Australian Air Quality Forecasting System (AAQFS – Cope *et al*., 2002, 2003), and the other is CSIRO's The Air Pollution Model (TAPM – Hurley 1997, 1999, 2002; Hurley *et al*., 2002, 2005). The AAQFS consists of the Limited Area Prediction System (LAPS – Puri *et al*., 1998) that provides meteorological forecasts, nested down to a 5km resolution from the regional forecasts, and the CSIRO Chemical Transport Model (CTM – Cope *et al*., 1998) that provides air pollution forecasts for up to two days. CTM is capable of zooming to a 1-km resolution for a range of pollutant species that include nitrogen dioxide, ozone, particles and several air toxics. The AAQFS is currently run daily for Melbourne and Sydney by the Australian Bureau of Meteorology. The other model, TAPM, is a PC-based, prognostic meteorological and air pollution model driven by a Graphical User Interface. It is a fast, operationally easy to use modelling system. However, it still contains comprehensive science. It includes a nested approach for meteorology and air pollution, which allows a user to zoom-in the simulation to a local region of interest. The meteorological component of the model is nested within synoptic-scale analyses/prognoses that drive the model at the boundaries of the outer grid. The use of integrated plume rise, Lagrangian particle, building wake, Eulerian grid, and condensed chemistry modules, allows industrial plumes and/or urban emissions to be modelled at fine resolution for long simulations (e.g. one year). The only user-supplied data required for air pollution applications are emission information (point, line, area/volume, or gridded emissions).

TAPM has been extensively evaluated against a wide range of observed meteorological and air pollution situations that include seasonal variations of photochemical smog episodes in Melbourne (Hurley, 2000), meteorological case studies in Kwinana (Hurley and Luhar, 2000), events of transport of pollutants from Melbourne to Cape Grim (Cox *et al*., 2000), year-long meteorology and air pollution concentrations for the industrial area of Kwinana (Hurley *et al*., 2001), year-long urban meteorology, photochemical smog and particulates in Melbourne (Hurley *et al*., 2003), meteorology and air pollution in the Pilbara and Port Hedland regions (Physick *et al*., 2002a), year-long urban meteorology and photochemical smog in Perth (Physick *et al*., 2002b), urban meteorology and air pollution on high ozone days in Brisbane (Ischtwan, 2002), and meteorology and air pollution for the Kincaid, Indianapolis and Kwinana tracer datasets (Luhar and Hurley, 2002, 2003, 2004).

In particular, the Melbourne verification study of Hurley *et al*. (2003) demonstrated that a prognostic approach (TAPM) could be used to successfully model year-long urban meteorology and photochemical dispersion for regulatory applications, in contrast to studies that model selected worst-case events. This approach allows meteorology, ozone, nitrogen dioxide and particles (PM2.5 and PM10) to be modelled to produce annual pollution statistics. The results of the Melbourne verification study showed that annual extreme (high) concentrations could be modelled accurately (to within a few tens of percent of observations), when a high quality urban emission inventory is available. The study also showed that running the model both with and without assimilating a network of near-surface wind observations made little difference to the annual statistics.

A combined approach of using TAPM meteorology to drive various photochemical transport models has been used by Australian EPA's to model case studies of high photochemical smog for both present and future emission scenarios. Some examples are Ischtwan (2002) using CIT for Brisbane and Burgers *et al*. (2003) using SAQM for Melbourne, while CIT has been used for Sydney, TAPM for Adelaide, and a number of these models as well as in-house developed models have been used for Perth. A combination of TAPM meteorology and the CTM from the AAQFS has recently been developed into TAPM-CTM, which allows the CTM to be configured and run from the TAPM GUI using TAPM meteorology. The CTM allows a number of the common photochemical mechanisms to be used (e.g. LCC used in CIT, CBIV used in SAQM). The TAPM-CTM system is currently being assessed by EPA's in a number of Australian states.

The Regional Atmospheric Modelling System (RAMS) has been the model of choice for another series of studies into the local land sea breeze circulation and photochemical smog in Perth (Ma Yimin and Lyons 2000, 2003). Using high resolution simulations with RAMS, the model revealed the influence of the synoptic scale thermal trough on the sea breeze in the Perth region which results in a wider distribution of pollution across this region.

URBAN-SCALE MODELLING IN NEW ZEALAND

Brief Background

Despite its clean green image, New Zealand's urban areas can experience severe degradation in air quality and visibility. Photochemical smog does not appear to be an issue in New Zealand, although Brasell (1982) reported 15 days during the summer of 1979/80 when elevated ozone levels were measured. Attention has been mostly paid to the problem of particulate matter less than ten microns (PM10). For some urban areas, daily-averaged concentration of PM10 frequently exceeds guideline values of 50 μg m^{-3} in winter months. PM10 pollution occurs not only in larger urban areas such as Auckland and Christchurch, but also in smaller towns like Timaru – which has a population of only 27,000. Similar to

Australian cities, prognostic modelling has shown that pollution events may occur under sea breeze conditions, as pollutants out at sea are recirculated back over land during the daytime (McKendry, 1989, 1992).

Perhaps the most researched and severe air pollution episodes occur in the city of Christchurch, situated in the South Island. These episodes can result from the injection of PM10, produced by burning of solid fuels from home heating, into shallow nocturnal inversion layers during clear nights. A significant number of investigations, based on the integration of numerical simulations and measurements of meteorology and air quality, have been carried out over the past five years in order to evaluate the major factors that influence the Christchurch urban air quality. These studies are summarised in the next section.

Modelling efforts

A major challenge for modelling endeavours in New Zealand – especially in the South Island where the Southern Alps dominate the landscape – is the complex mountainous topography. The terrain-following coordinate system employed by prognostic models is not really suited for such environments, particularly when high-resolution (i.e. less than 5-km) simulations are performed (Pielke, 2002). Regardless, several researchers have successfully modelled the meteorology and dispersion of pollution in this country (Barna and Gimson, 2000, 2002; Zawar-Reza and Sturman, 2002, Titov, 2004).

The Christchurch Air Pollution Study 2000 (CAPS 2000; Spronken-Smith *et al*., 2002) consisted of a major field experiment during which meteorological and air pollution data were collected, providing the basis for model evaluation. Initial empirical results have been described by Kossmann and Sturman (2004), while modelling work is ongoing. A more recent study of the relationship between air pollution and health (Health and Air Pollution in New Zealand – HAPiNZ; see www.hapinz.org.nz) has also been initiated, including a major objective to develop exposure maps for urban areas using TAPM and Mesoscale Model/ Comprehensive Air Quality Modelling system (MM5/CAMx4; Grell *et al*., 1992; ENVIRON, 2003).

Before 1999, models with detailed chemistry had not been applied to New Zealand cases. McKendry *et al*., (1986) provided the first attempt at simulation of the complex north-easterly winds over Christchurch with CSUMM. Later, van den Assem (1997) used RAMS to study two wintertime PM10 haze episodes. His high-resolution simulations captured the effect of cold air drainage winds (down-slope winds) from the sloping terrain surrounding Christchurch and their role in contributing to the spatial heterogeneity of pollution concentrations. Verification of the simulated winds showed the model was able to predict the main airflow characteristics of significance for air pollution dispersion. Predicted variations in PM10 concentrations also compared well with observations. Simulated meteorology of RAMS has also been used by Barna and Gimson (2002) to drive the CALMET/CALPUFF modelling system for a polluted night in Christchurch (CALMET is a diagnostic meteorological model, and CALPUFF is its associated air quality dispersion module; Scire *et al*., 1999). This method is termed a hybrid approach since the simulated meteorology from the prognostic model is used to drive the diagnostic model (Godfrey, 2002).

RAMS was used by Sturman and Zawar-Reza (2002) to perform high-resolution simulations for the three most common surface wind regimes over Christchurch that can lead to elevated PM10 levels (i.e. north-easterly, weak southerly and weak north-westerly). Modelled wind fields were used to construct back-trajectories in order to determine the distance air travelled during a typical air pollution episode. The back-trajectories were then used as subjective guideline to determine a clean air zone boundary around the city. Currently, work is underway to construct PM10 exposure maps for Christchurch by performing long-term runs with TAPM. However, the poor spatial and temporal resolution of the available emissions inventory in Christchurch poses challenges to this undertaking (Zawar-Reza *et al*., 2005a). Model intercomparison studies between TAPM and MM5/CAMx4 have shown that the more sophisticated MM5/CAMx4 system performs better in the case of Christchurch, although the convenient computational requirements for TAPM still make it a very attractive tool (Zawar-Reza *et al*., 2005b).

For Auckland, modelling of photochemical pollution in the Auckland region has been carried out primarily with diagnostic tools such CALMET/CALGRID (Gimson, 2000a, 2005). Yet, the Auckland simulations were further refined with the addition of prognostic model output using RAMS to provide additional information for data sparse regions (Gimson 2000b). However, TAPM has also been applied for simulation of air quality (Gimson and Scoggins 2002). These simulations confirm conclusions reached by previous work and show that elevated levels of ozone frequently appear, but they usually occur at sea, and that elevated levels are measured only when sea breeze recirculates air under weak synoptic conditions.

SUMMARY

Development of urban-scale air quality models based on prognostic approaches has closely followed developments in computer technology. These models have been used extensively in Australia and New Zealand, and are increasingly being used as a tool to address air quality issues in both countries. It is predicted that they will eventually replace the traditional, simplistic Gaussian approach to modelling air pollution dispersion in air quality management and regulation procedures. Up to now, they have formed the basis for study of photochemical smog in coastal cities in Australia, whereas in New Zealand they are mostly used to simulate PM10 dispersion. They are currently being used to produce high resolution maps of human exposure to air pollution, as well as to predict more accurately the chemical changes that take place in the atmosphere over urban areas. The main limitation to progress in the application of these prognostic models to air pollution dispersion appears to be the poor reliability and resolution of emission inventories.

REFERENCES

Abbs D.J. and Physick W.L., 1992. Sea breeze observations and modelling: A review, *Australian Meteorological Magazine*, **41**, 7-19.

Arya P.S. (1999). *Air pollution meteorology and dispersion*. Oxford University Press, 310pp.

Barna M. and Gimson N.R., 2000. Application of the RAMS/CALMET/ CALPUFF airshed model in Christchurch, New Zealand, 1*5th International Clean Air and Environment Conference*. Clean Air Society of Australia & New Zealand, pp. 10-14.

Barna M.G. and Gimson N.R., 2002. Dispersion modelling of a wintertime particulate pollution episode in Christchurch, New Zealand, *Atmospheric Environment*, **36**, 3531-3544.

Burgers M., Ng Y., Boyle R., Cope M. and Hurley, P., 2003. Ozone event modelling for the Melbourne Air Quality Improvement Plan, *Proceedings of the National Clean Air Conference of CASANZ*, Newcastle, Australia, 23-27 November 2003.

Cope M.E., Carnovale F., and Johnson M., 1990. An air quality modelling system for oxidant transport and production in the Port Philip control region, *Proceedings 10th International Conference Clean Air and Environment*, Auckland, New Zealand, Clean Air Society of Australia and New Zealand, pp. 165-170.

Cope M. E. and Hess D., 1998. The application of an integrated meteorological air quality modelling system to a photochemical smog event in Perth, Australia, S.-E. Gryning and N. Chaumerliac, eds., *Air Pollution Modeling and its Application XII*, Plenum Press, 609-616.

Cope M. E., Manins P., Hess D., Mills G., Puri K., Dewundege P., Tilly K., and Johnson M., 1998. Development and application of a numerical air quality forecasting system, *Proceedings 14th International Conference Clean Air and Environment*, Melbourne, 18-22 October 1998, Clean Air Society of Australia and New Zealand, pp. 353-358.

Cope M.E., Hess G.D., Lee S., Manins P.C., Puri K., Tory K. and Young M., 2002. The Australian Air Quality Forecasting System. A review of photochemical smog forecasting capability, *Proceedings 12th Conference on the Applications of Air Pollution Meteorology with A&WMA*, 20-24 May 2002, Norfolk, VA.

Cope M.E., Lee S., Manins P.C., Puri K., Azzi M., Carras J., Lilley W., Hess G.D., Tory K., Nelson P., 2004. The Australian Air Quality Forecasting System. Part I. Project description and early outcomes, *Journal of Applied Meteorology*. **43**, 649-662.

Cox M., Hurley P., Fraser P., and Physick W., 2000. Investigation of Melbourne region pollution events using Cape Grim data, a regional transport model (TAPM) and the EPA Victoria carbon monoxide inventory. *Clean Air and Environmental Quality*, **33**, 35-40.

ENVIRON International Corporation, 2003, Comprehensive Air quality Model with extensions (CAMx), version 4.00, Novato, California.

Garratt J.R. 1994. Review: the atmospheric boundary layer, *Earth-Science Reviews*, **37**, 89-134.

Gimson N.R., 2000a. Model simulation of the air quality of Auckland, *Clean Air and Environmental Quality*, **34**, 37-42.

Gimson N.R., 2000b. Urban airshed modelling in Auckland: recent developments, *Proceedings of the 15th International Clean Air and Environment Conference*, Eastwood, New South Wales, Australia, 68-72pp.

Gimson N.R. 2005. Modelling the air quality of Auckland – application to changing emissions in an ozone-limited atmosphere, *Clean Air and Environmental Quality*, **39**, 32-38.

Gimson N.R and Scoggins A., 2002. Urban airshed modelling and exposure mapping in Auckland, *Proceedings of the 16th International Clean Air and Environment Conference*, Christchurch, New Zealand, pp. 241-245.

Godfrey J. 2002. A method for better wind fields for air quality applications in complex atmospheric environments at fine scales, Proceedings of the *16th International Clean Air and Environment Conference*, Christchurch, New Zealand, pp. 246-252.

Grell G.A., Dudhia J., and Stauffer D., 1994. A description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5), NCAR Tech Note NCAR/TN-398+STR, 138 pp.

Harley R.A., Russell A.G., McRae G.J., Cass G.R. and Seinfeld J.H., 1993. Photochemical modelling of the southern California air quality study, *Environmental Science Technology*, **27**, 378-388.

Hurley P.J. and Physick W.L., 1990. Fumigation modelling - a Lagrangian particle approach, International Journal of *Mathematics and Computers in Simulation*, **32**, 65-70.

Hurley P.J. and Physick W.L,. 1991. A Lagrangian particle model of fumigation by breakdown of the nocturnal inversion. *Atmospheric Environment*, **25A**, 1313-1325.

Hurley P.J. and Physick W.L. 1993. A skewed, homogeneous Lagrangian particle model for convective conditions, *Atmospheric Environment*, **27A**, 619-624.

Hurley P.J. and Physick W.L,. 1993. Lagrangian particle modelling of buoyant point sources - plume rise and entrapment in convective conditions, *Atmospheric Environment*, **27A**, 1579-1584.

Hurley P.J., 1994. PARTPUFF – A Lagrangian particle/puff approach for plume dispersion modelling applications, *Journal of Applied Meteorology*, **33**, 285-294.

Hurley P., 1997. An evaluation of several turbulence schemes for the prediction of mean and turbulent fields in complex terrain. *Boundary-Layer Meteorology*, **83**, 43-73.

Hurley P., 1999. *The Air Pollution Model (TAPM) Version 1*: Technical description and examples. CSIRO Atmospheric Research Technical Paper No. 43

Hurley P., 2000. Verification of TAPM meteorological predictions in the Melbourne region for a winter and summer month, *Australian Meteorology Magazine*, **49**, 97-107.

Hurley P. 2002. The Air Pollution Model (TAPM) Version 2. Part 1: Technical description. CSIRO Atmospheric Research Technical Paper No. 55. Available at http://www.dar.csiro.au/TAPM.

Hurley P.J. and Manins P.C. 1995. Meteorological Modelling on high ozone days in Perth, Western Australia, *Journal of Applied Meteorology*, **34**, 1643-1652.

Hurley P., Noonan J. and Manins P. 1996a. Meteorological Modelling in Sydney Australia: case study of a smog event. *Air Pollution Modelling and its Application XI*, Edited by S-V. Gryning and F.A. Schiermeier, Plenum Press, New York, 1996.

Hurley P., Manins P. and Noonan J. 1996b. Modelling Wind Fields in MAQS. *Environmental Software*, **11**, 35-44.

Hurley P. and Luhar A., 2000. The Kwinana Coastal Fumigation Study: Meteorological and turbulence modelling on selected days. *Boundary-Layer Meteorology*, **94**, 115-138

Hurley P., Blockley A., and Rayner K., 2001. Verification of a prognostic meteorological and air pollution model for year-long predictions in the Kwinana region of Western Australia. *Atmospheric Environment*, **35**, 1871-1880.

Hurley P., Physick W. and Luhar A., 2002. The Air Pollution Model (TAPM) Version 2. Part 2: Summary of some verification studies. CSIRO Atmospheric Research Technical Paper No. 57. Available at http://www.dar.csiro.au/TAPM.

Hurley P., Manins P., Lee S., Boyle R., Ng Y. and Dewundege P. 2003. Year-long, high-resolution, urban airshed modelling: Verification of TAPM predictions of smog and particles in Melbourne, Australia, *Atmospheric Environment*, **37**, 1899-1910.

Hurley P., Physick W. and Luhar A. 2005. TAPM – A practical approach to prognostic meteorological and air pollution modelling, *Environmental Modelling & Software*, **20**, 737-752.

Ischtwan, J. 2002. Prognostic modelling of a period of summer photochemical smog in south-east Queensland, *Proceedings of the 16th International Clean Air and Environment Conference of CASANZ*, Christchurch, New Zealand, 19-22 August 2002.

Jacobson M.Z. 2000, *Fundamentals of atmospheric modelling*, Cambridge University Press, 656pp.

Kossmann, M. and Sturman, A. 2004. The surface wind field during winter smog nights in Christchurch and coastal Canterbury, New Zealand, *International Journal of Climatology*, **24**, 93-108.

Kowalczyk E.A. and McGregor J. L. 2000. Modelling trace gas concentrations at Cape Grim using the CSIRO Division of Atmospheric Research Limited Area Model (DARLAM). J*ournal of Geophysical Research*, **105 (D17)**: 22167-22183.

Lu H. and Shao S.Y., 2001. Toward quantitative prediction of dust storms: an integrated wind erosion modelling system and its application, *Environmental Modelling & Software*, **16**, 233-249.

Luhar A. and Hurley P., 2002. Comparison of meteorological and dispersion predictions obtained using TAPM with the Indianapolis (urban), Kincaid (rural) and Kwinana (coastal) field data sets, *Proceedings of the 8th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, Sofia, Bulgaria, 14-17 October 2002.

Luhar A., and Hurley P., 2003. Evaluation of a 3-d prognostic meteorological and dispersion model, TAPM, using the Indianapolis (urban) and Kincaid (rural) point-source data sets, *Atmospheric Environment*, **37**, 2795-2810.

Luhar A. and Hurley P., 2004. Application of a prognostic model TAPM to sea-breeze flows, surface concentrations, and fumigating plumes, *Environmental Modelling & Software*, **19**, 591-601.

Ma Yimin and Lyons T.J., 2000. Numerical simulation of a sea breeze under dominant synoptic conditions at Perth, *Meteorology and Atmospheric Physics*, **63**, 89-103.

Ma Yimin and Lyons T.J., 2003. Recirculation of coastal urban air pollution under a synoptic scale thermal trough in Perth, Western Australia, *Atmospheric Environment*, **37**, 443-454.

Mahrer Y. and Pielke R.A. 1977. A numerical study of the airflow over irregular terrain, *Beitraege zur Physik der Atmosphaere*, **50**, 98-113.

McKendry I.G., Sturman A.P. and Owens I.F. 1986. A study of interacting multi-scale wind systems, Canterbury Plains, New Zealand, *Meteorology and Atmospheric Physics*, **35**, 242-252.

McKendry I.G., 1989. Numerical simulation of sea breezes over the Auckland region, New Zealand – air quality implications. *Boundary-Layer Meteorology*, **49**, 7-22.

McKendry I.G., 1992. Numerical simulation of sea breeze interactions over the Auckland region, New Zealand, *New Zealand Journal of Geology and Geophysics*, **35**, 9-20.

McNider R.T. and Pielke R.A., 1981. Diurnal boundary-layer development over sloping terrain, *Journal of Atmospheric Science*, **38**, 2198-2212.

Pielke, R.A., 2002. *Mesoscale meteorological modelling. 2nd ed*. Academic Press, 676pp.

Physick W.L., 1996. Photochemical smog studies in Australian cities, In: Urban Air Pollution, Eds., Power H. and Moussiopoulos, 141-184.

Physick W.L. and Abbs D.J., 1991. Modelling summertime dispersion in the coastal terrain of southeastern Australia, *Monthly Weather Review*, **119**, 1014-1030.

Physick W.L., Noonan J.A., McGregor J.L., Hurley P.J., Abbs D.J. and Manins P.C. 1994. *LADM: A Lagrangian Atmospheric Dispersion Model*, CSIRO Atmospheric Research Technical Paper No. 24. 137 pp.

Physick, W.L. and Hurley P.J., (1994). A fast Lagrangian particle model for use with three-dimensional mesoscale models, *Air Pollution Modelling and its Application X*, Edited by S-V. Gryning and M.M. Millan, Plenum Press, New York, 1994.

Physick W.L., Noonan J.A., Manins P.C., Hurley P.J. and Malfroy H. (1992). Application of coupled prognostic windfield and Lagrangian dispersion models for air quality purposes in a region of coastal terrain, *Air Pollution Modelling and its Application IX*, Edited by H. van Dop and G. Kallos, Plenum Press, New York, 725-729.

Physick W.L., Hurley P.J. and Manins P.C. (1995). An environmental impact assessment of industrial development at Gladstone, Australia, *International Journal of Environment and Pollution*, **5(4-6)**, pp. 548-556.

Physick W., Blockley A., Farrar D., Rayner K. and Mountford P., (2002a). Application of three air quality models to the Pilbara region, *Proceedings of the 16th International Clean Air and Environment Conference*, Christchurch, New Zealand, 18-22 August 2002.

Physick W., Cope M. and Stuart A., (2002b). Evaluation of a population-surrogate emissions inventory for Perth using TAPM, *Proceedings of the 16th International Clean Air and Environment Conference*, Christchurch, New Zealand, 18-22 August 2002.

Puri K., Dietachmayer G.S., Mills G.A., Davidson N.E., Bowen R.A. and Logan L.W. 1998. The BMRC Limited Area Prediction System, LAPS, *Australian Meteorology Magazine*, **47**, 203-223.

Scheffe R.D. and Morris R.E., 1993. A Review of the Development and Application of the Urban Airshed Model, *Atmospheric Environment*, **27B**, 23-39.

Scire J., Robe F., Fernau M. and Yamartino R. 1999. *A User's Guide for the CALMET Meteorological Model (Version 5.0)*, Earth Tech, Concord, Massachusetts.

Sillman S., 1999. The relation between ozone, NO_x and hydrocarbons in urban and polluted rural environments, *Atmospheric Environment*, **33**, 1821-1845.

Spronken-Smith R.A., Sturman A.P., Kossmann M. and Zawar-Reza, P. 2002. An overview of the Christchurch Air Pollution Study (CAPS) 2000', *Proceedings of the 16th International Clean Air and Environment Conference,* Christchurch, New Zealand, 18-22 August 2002.

Stull R.B., 1998. *An introduction to boundary layer meteorology*, Springer, New York.

Sturman A.P. and Zawar-Reza P. 2002. Application of back-trajectory techniques to the delimitation of urban clean air zones, *Atmospheric Environment*, **36**, 3339-3350.

Titov M., 2004. *Application of an atmospheric mesoscale modelling system to analysis of air pollution dispersion in the Christchurch area*, Masters Thesis, University of Canterbury, Department of Geography, Christchurch, New Zealand.

US Environmental Protection Agency 1986. *Guideline on air quality models (revised). US Environmental Protection Agency*, Office of Air Quality Planning and Standards Report No. EPA 450/2-78-027R.

Van den Assam S. 1997. *Dispersion of air pollution in the Christchurch area*, Ph.D. Thesis, University of Canterbury, Department of Geography, Christchurch, New Zealand.

Wright N. and Baker C.J. 2002. Environmental applications of computational fluid dynamics, In: *Environmental modelling, finding simplicity in complexity*, ed. J. Wainwright and M. Mulligan, John Wiley and Sons Publishing.

Zawar-Reza P., Kingham S. and Pearce J., 2005a. Evaluation of a year-long dispersion modelling of PM10 using the mesoscale model TAPM for Christchurch, New Zealand, *Science of the Total Environment*, (in press).

Zawar-Reza P., Titov M. and Sturman A.P., 2005b. Dispersion modelling of PM10 for Christchurch, New Zealand: an intercomparison of performance between Mesoscale Model (MM5) and The Air Pollution Model (TAPM), *Proceedings of the 17th International Clean Air and Environment Conference*, Hobart, Australia, 3-6 May 2005.

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