ELSEVIER

Journal of Wind Engineering
and Industrial Aerodynamics 67&68 (1997) 363–372

JOURNAL OF wind engineering AND industrial aerodynamics

# Use of meteorological models in computational wind engineering

Roger A. Pielke Sr.*, Melville E. Nicholls

*Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523, USA*

**Abstract**

Computational wind engineering has progressed considerably in recent years. Along with the improved capability to simulate the small-scale flows around architectural structures there is a need to more realistically simulate the larger-scale atmospheric flows in which they are embedded. This would greatly expand the application of numerical models in areas of overlap between the disciplines of atmospheric science and wind engineering. This paper reviews the basic equations used by meteorological models, modifications required to incorporate buildings and how nested grids can be used to span the gap between large separations in scale. Areas requiring future research and model development are discussed and potential applications of a model which can simulate both large-scale meteorological flows as well as small-scale flows around buildings are suggested.

*Keywords:* Meteorological modeling; Atmospheric modeling

## 1. Overview of meteorological models used in computational wind engineering

### *1.1. Basic equations*

The development of equations used in meteorological models is discussed in a variety of references beginning with the seminal study of Richardson [1]. Recent summary texts include those of Pielke [2] and Krishnamurti and Bounoua [3].

The physical equations used in atmospheric simulation codes are:

1. A prognostic vector of motion equation defined for a rotating sphere (i.e., the earth). External forces include the pressure gradient force and gravity. The apparent force that results from the coordinate transformation to a rotating system is called the Coriolis force.
2. The ideal gas equation (a diagnostic relation).

* Corresponding author. E-mail: dallas@hercules.atmos.colostate.edu.


*PII* S0167-6105(97)00086-X

3. A prognostic equation for heat defined in terms of potential temperature. Potential temperature is the temperature that would occur if an air parcel were compressed or expanded to a reference pressure level; usually $10^5$ Pa. Potential temperature is directly related to entropy.
   Sources and sinks of heat include those related to phase changes of water, radiative flux divergence, and exchanges from the land, ocean, and ice surfaces.
4. A prognostic equation for water in its three phases: solid, liquid, and vapor. Water is converted among the phases by sublimation, deposition, evaporation, condensation, and transpiration, and is exchanged with the surface. During the conversion heat is released or absorbed.
5. A prognostic equation for other atmospheric trace gases which includes chemical conversions and phase changes. Examples of these trace gases include sulphur dioxide, carbon monoxide, radon, etc.
6. A prognostic equation for mass of air.

Various approximations are made when these equations are applied to specific atmospheric features. For operational weather forecast models, for example, vertical accelerations are neglected and the vertical equation of motion reduces to a diagnostic hydrostatic pressure equation. Moreover, the conservation of mass equation is also often reduced to a diagnostic equation in which either the total or local time tendency of density is neglected. A comprehensive review of the equations and assumptions frequently used in atmospheric models is given in Ref. [4].

For computational wind engineering, the complete three-dimensional equation of motion must be retained since dynamic pressures are essential for the accurate simulation of small-scale flow. Density fluctuations in the conservation of mass equation are ignored, however, for flow that is substantially subsonic.

### *1.2. Examples*

There have been only a limited number of applications of meteorological models to wind engineering problems. Much of this neglect is undoubtedly related to different educational tracks of atmospheric scientists (generally, in a physical science framework) and of engineers. However, since wind engineers and atmospheric scientists work with the same media (i.e., the atmosphere) this void is ripe for substantial scientific achievement.

In the context of physical wind tunnel modeling and numerical modeling, Avissar et al. [5] provided a framework where the capabilities of those two tools overlap. Nicholls et al. [6,7] provided specific examples of improved understanding when a meteorological model is used to simulate airflow over buildings (results from those studies are discussed further in Section 2).

### *1.3. Procedure of application*

Atmospheric numerical models can include large-scale effects such as propagating weather features, rotational effects of the earth, cloud processes, etc. which can be nested down to very small scales of direct relevance to wind engineers. Grasso [8], for example, used six successively finer-scale nests to scale down from regional-scale atmospheric flow to the tornado scale. Ziegler et al. [9] applied four nests to scale down to deep cumulonimbus clouds in which details of the low-level flow were represented. Eastman [10] used two nests to scale down to the eyewall region of Hurricane Andrew in 1992 in which the rapid intensification of the system was realistically modeled. Poulos [11] is using two nests to "telescope down" over the front range of Colorado in order to simulate adequately the local terrain that very substantially influences pollution dispersion from Rocky Flats.

Detailed representations of the atmospheric boundary layer are also a capability of these tools. Such models on that scale are referred to as large eddy simulation (LES) models. Examples include Refs. [12–16].

The procedures to apply atmospheric models to wind engineering studies can be summarized as follows.

- Use grid nesting in a prognostic meteorological model to telescope down in a specific site of interest.
- Use a fine enough spatial scale to represent buildings including roofs and walls.
- Use the wind and turbulence fields provided by the finest model grid as input to physical models of more detailed building structure features.

## 2. Application to airflow and dispersion around buildings

Models which can simulate both meteorological processes as well as the small-scale flow around buildings have many potential applications. The LES models developed by the wind engineering community to study the flow around buildings and mesoscale meteorological models have many aspects in common. For instance, the numerical techniques used to solve the governing equations and the physical parameterization of subgrid-scale fluxes are very similar. Therefore, it is not necessary to couple a building model and a meteorological model together in some fashion, since to a large extent, the difference between them is the scale of fluid motion to which they are typically applied. A way of bridging the gap between these scales is through the use of multiple nested grids [17]. This enables large-scale meteorological flow patterns to be simulated and by using multiple nested grids to telescope down in scale, the resultant airflow around architectural structures can also be investigated.

The Colorado State University Regional Atmospheric Modeling System (RAMS) is a meteorological model with nested grid capability [6,18]. It employs parameterizations of meteorologically important physical processes, such as surface fluxes, radiation, and microphysics, as well as initialization procedures for incorporating standard weather observations, representation of orography and appropriate boundary conditions. The method for representing buildings in the model is similar to that discussed in Ref. [19]. The normal component of velocity is set to zero on the roofs and walls of the building. A logarithmic function is used to give the relation between the velocity at the grid point adjacent to the surface and the surface shear stress. At the corners of the building, the momentum fluxes are determined by the scheme described in Ref. [6]. When applied to simulate the flow around buildings, this model is an LES model similar to those developed by the wind engineering community. Several investigators have used the LES method to simulate flow around buildings [6,19–22] and it has been found to produce greater accuracy than statistical turbulence models [23]. Most of the testing of LES models has been for the situation of an incident flow perpendicular to a face of the building. However, wind tunnel and field experiments have shown that the maximum wind loads on a roof occur for an oblique incident flow and are associated with the formation of corner conical vortices [24–29]. Therefore, it is important that LES models are tested to see if they are capable of realistically simulating these features. As a test of the RAMS building model, Nicholls et al. [6] attempted to simulate corner conical vortices and had some limited success, although computational limitations precluded the simulation from being run long enough to obtain results which could be statistically analyzed and compared with wind tunnel and field data. Several corner conical vortices formed during the simulation which appear to have some realistic features. Since they are small in scale relative to the height of the building, a large number of grid points were required to resolve them. The fine grid had 80 × 80 × 72 grid points and was embedded in the center of a coarse grid with a similar number of grid points. The grid increment was 1 m for the fine grid and 3 m for the coarse grid. The building was centered within the fine grid and was a cube with 60 × 60 × 60 grid points. Cyclic boundary conditions were prescribed on the coarse grid. As body-induced eddies shed from the building advected through the downstream boundary, they re-emerge at the upstream boundary, eventually producing a turbulent flow field. Fig. 1 shows the pressure perturbation on the roof at

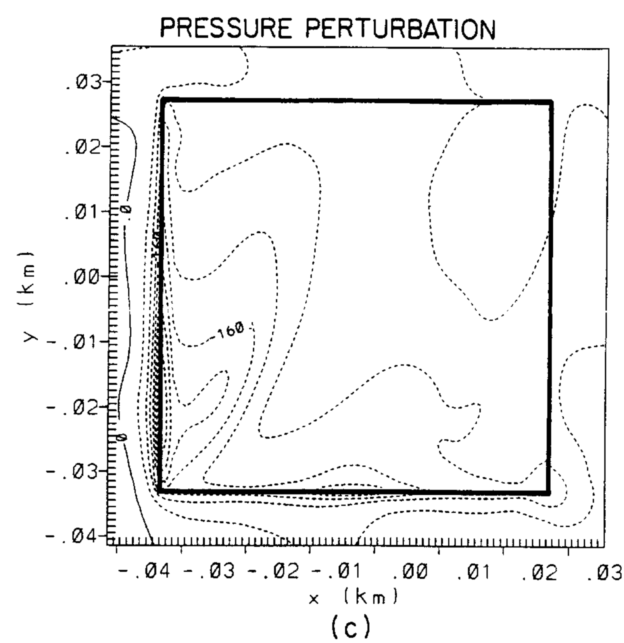


Fig. 1. Pressure perturbations at roof level on a cubic building defined by the thick solid line. The contour interval is 40 Pa.

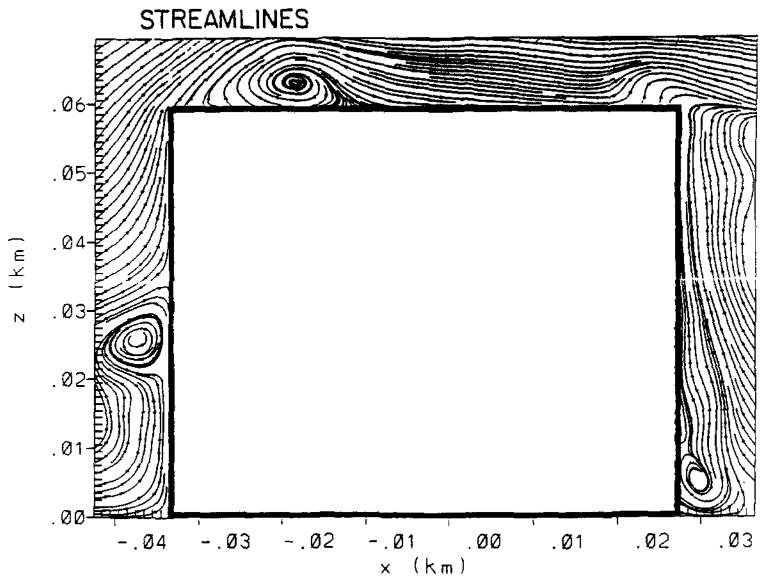


Fig. 2. Streamlines for a vertical cross section through the center of the building showing the roof corner conical vortex.

$t = 80$ s for the fine grid. The wind direction is 225° towards the lower left corner in this figure. At an angle of about 20° to the left edge of the roof is the centerline of a corner conical vortex identifiable in this figure by a relative minima of pressure. The lowest pressure perturbation occurs about a fifth of the way along the left edge of the roof. The corner conical vortices were transient features in this highly turbulent flow field, often being well defined on one side of the roof while virtually disappearing on the other side. Fig. 2 shows an $x/z$ cross section of streamlines through the center of the building which illustrates the well-defined corner conical vortex at $t = 80$ s.

As an example of the application of multiple nested grids to span a wide range of spatial scales, Nicholls et al. [7] conducted a two-dimensional simulation of a microburst-producing thunderstorm and the resultant airflow around a building. Five grids were used with grid increments of 202.5, 67.5, 22.5, 7.5, and 2.5 m. Each successively finer grid was centered within the next coarsest grid with the building centered within the finest grid. The model was initialized using the 2300 UTC 2 August 1985, Dallas-Ft. Worth, Texas microburst sounding used by Proctor [30]. Only the coarsest grid was activated while the thunderstorm developed. When the thunderstorm generated a microburst, the four finer-scale grids were activated. The microburst propagated into the finer grids enabling the small-scale flow around the building to be investigated. Fig. 3 shows the temperature perturbation field at $t = 5400$ s for grid 2. A cold outflow from the thunderstorm can be seen near the surface. The building is just discernible in this figure, centered at $x = 0.3$ km. Fig. 4 shows the streamlines at $t = 5400$ s for grid 3. This shows the microburst vortex centered at a height of 0.8 km and a smaller clockwise rotating vortex which has been shed from the building. There

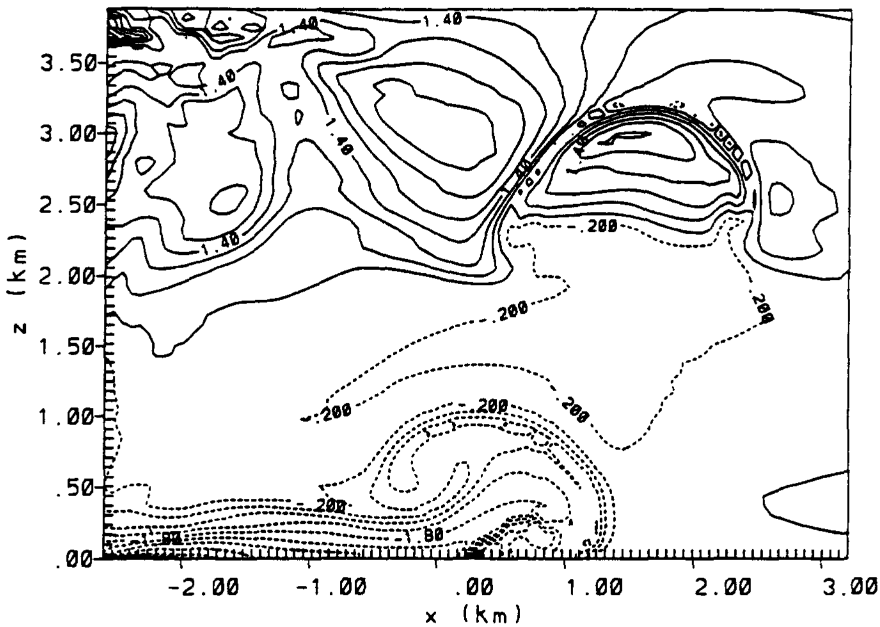


Fig. 3. The temperature perturbation field at $t = 5400$ s for grid 2. The contour interval is 0.4 K.

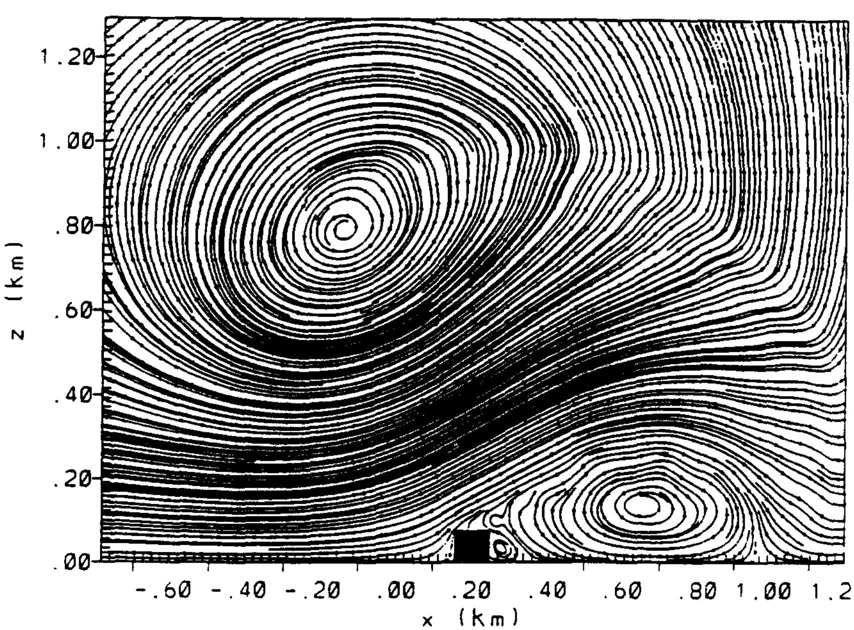


Fig. 4. Streamlines for grid 3 at $t = 5400$ s.

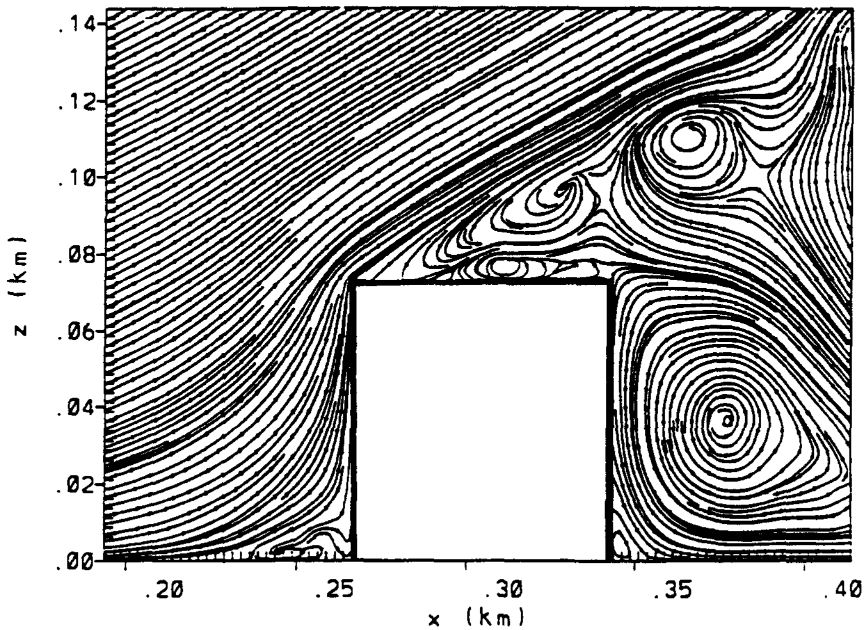


Fig. 5. Streamlines for grid 5 at $t$ = 5400 s.

are two finer grids which further "telescope down" in scale. Fig. 5 shows the streamlines at $t$ = 5400 s for the finest grid. Separation has occurred at the windward corner of the building. The clockwise rotating eddy which formed behind the building, seen in grid 3, has already advected out of the fine grid. For the simulated microburst, there are actually two wind maxima which occur near the surface. The first strong wind gust is at the leading edge of the outflow, while the second wind maxima is directly beneath the low-pressure center aloft. It is well known that pressure gradients can affect where separation occurs for flow over a flat plate and on the rate at which the boundary layer thickness grows. There was some indication that the large-scale pressure gradient associated with the microburst vortex may have had an effect on the angle the separated flow made with the roof.

Mesoscale meteorological models sometimes utilize dispersion models in order to study how pollutants are transported and their sources and receptors. The Lagrangian particle dispersion model (LPDM) developed in Refs. [31,32] is one such model. It can simulate the release and dispersion of a number of non-buoyant, passive pollutants from multiple sources of various geometries. The LPDM utilizes frequently written out data files created during the mesoscale model simulation. It runs very quickly and can be used to investigate many different release scenarios. Examples of the use of the LPDM can be found in the studies in Refs. [33–35]. Murakami et al. [36] presented results of a LES of the turbulent diffusion of buoyant and heavy gases near a building. In this investigation, equations for the gaseous constituents were added to the LES model and solved during the model run. This approach is inherently more accurate than using a LPDM, but is more computationally intensive and does not have the flexibility for simply investigating many different release scenarios. Lee and Naslund [37] employed a LPDM to investigate dispersion around buildings using the mean flow field simulated by a $\kappa$–$\varepsilon$ model. In future, it is to be expected that LPDMs will be employed to investigate dispersion around buildings using the time-dependent flow field simulated by an LES model.

## 3. Future opportunities

Some important areas of research and model development need to be addressed in order to acquire confidence in the validity of a meteorological model designed for use in wind engineering and to make it a useful tool for investigating a wide range of problems:

1. It needs to be tested at building scales by detailed comparison with CWE models and observations for a variety of flow scenarios.
2. A procedure for incorporating architectural structures of arbitrary shape, number, and alignments, which is compatible with the meteorological grid configuration needs to be developed and tested.
3. The turbulence structure of the flow field obtained in nested grid simulations needs to be compared with the observations for various flow scenarios. This knowledge would aid in choosing appropriate nested grid configurations so that realistic turbulence spectra are obtained for a particular problem.
4. The LPDM needs to be tested at building scale.

A model such as this would have applications to a large number of problems where knowledge of wind loading, turbulence, or dispersion of particles are required. It would be particularly useful for situations where accurate prediction of mesoscale flow fields is required. As an example, it could be used to investigate the dispersion of particles around a group of buildings situated in complex terrain for both convectively stable and unstable conditions.

In conclusion, the use of a meteorological model for application in wind engineering studies has been established. Increased computer capabilities in future years will permit additional detail in the representation of building structures in these models and continued research and development could well lead to a powerful tool for investigating a wide range of problems. The main obstacle at present is the continuation of financial research and development support for this marriage of atmospheric science and wind engineering technologies.

## Acknowledgements

This work was supported by the Army Research Office under Contract #DAAH04-94-G-0420 and by the Cooperative Program in Wind Engineering, NSF Grant #BCS-8821542. The typing of the paper and editorial review were very ably handled by Dallas McDonald.

## References


[1] L.R. Richardson, Weather Prediction by Numerical Process, Cambridge University Press, London, 1922, Reprinted by Dover, 236 pp.

[2] R.A. Pielke, Mesoscale Meteorological Modeling, Academic Press, New York, 1984, 612 pp.

[3] T.N. Krishnamurti, L. Bounoua, An Introduction to Numerical Weather Prediction Techniques, CRC Press Inc., Boca Raton, Florida, 1996, 293 pp.

[4] P. Thunis, R. Bornstein, Hierarchy of mesoscale flow assumptions and equations, J. Atmos. Sci. 53 (1996) 380–397.

[5] R. Avissar, M.D. Moran, R.A. Pielke, G. Wu, R.N. Meroney, Operating ranges of mesoscale numerical models and meteorological wind tunnels for the simulation of sea and land breezes, Bound.-Layer Meteor. (Special Anniversary Issue, Golden Jubilee) 50 (1990) 227–275.

[6] M.E. Nicholls, R.A. Pielke, J.L. Eastman, C.A. Finley, W.A. Lyons, C.J. Tremback, R.L. Walko, W.R. Cotton, Applications of the RAMS numerical model to dispersion over urban areas, in: J.E. Cermak et al. (Eds.), Wind Climate in Cities, Kluwer Academic Publishers, The Netherlands, 1995, pp. 703–732.

[7] M.E. Nicholls, R.A. Pielke, R.N. Meroney, Large eddy simulation of microburst winds flowing around a building, J. Wind Eng. Ind. Aerodyn. 46–47 (1993) 229–237.

[8] L. Grasso, Numerical Simulation of the May 15 and April 26, 1991 tornadic thunderstorms, Atmos. Sci. Paper #596, Colorado State University, Department of Atmospheric Science, Fort Collins, CO 80523, 1996, 151 pp.

[9] C.L. Ziegler, T.J. Lee, R.A. Pielke, Convective initiation at the dryline: a modeling study, Mon. Wea. Rev., 1996, submitted.

[10] J.L. Eastman, Numerical simulation of Hurricane Andrew – Rapid intensification, 21st Conf. on Hurricanes and Tropical Meteorology, 24–28 April 1995, Miami, Florida, AMS, Boston, 1995, pp. 111–113.

[11] G.S. Poulos, The interaction of katabatic winds and mountain waves, Ph.D. Dissertation, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523, 1996, in progress.

[12] U. Schumann, Direct and large eddy simulations of stratified homogeneous shear flows, Dyn. Atmos. Oceans 23 (1996) 81–98.

[13] R.L. Walko, W.R. Cotton, R.A. Pielke, Large-eddy simulations of the effects of hilly terrain on the convective boundary layer, Bound.-Layer Meteor. 58 (1992) 133–150.

[14] M.G. Hadfield, W.R. Cotton, R.A. Pielke, Large-eddy simulations of thermally-forced circulations in the convective boundary layer, Part I: a small-scale circulation with zero wind, Bound.-Layer Meteor. 57 (1991) 79–114.

[15] M.G. Hadfield, W.R. Cotton, R.A. Pielke, Large-eddy simulations of thermally forced circulations in the convective boundary layer, Part II: The effect of changes in wavelength and wind speed, Bound.-Layer Meteor. 58 (1992) 307–328.

[16] P.J. Mason, Large-eddy simulation: a critical review of the technique, Quart. J. Roy. Meteor. Soc. 120 (1994) 1–26.

[17] T.L. Clark, R.D. Farley, Severe downslope windstorm calculations in two and three spatial dimensions using anelastic interactive grid nesting: a possible mechanism for gustiness, J. Atmos. Sci. 41 (1984) 329–350.

[18] R.A. Pielke, W.R. Cotton, R.L. Walko, C.J. Tremback, W.A. Lyons, L.D. Grasso, M.E. Nicholls, M.D. Moran, D.A. Wesley, T.J. Lee, J.H. Copeland, A comprehensive meteorological modeling system – RAMS, Meteor. Atmos. Phys. 49 (1992) 69–91.

[19] S. Murakami, A. Mochida, K. Hibi, Three-dimensional numerical simulation of air flow around a cubic model by means of a large eddy simulation, J. Wind Eng. Ind. Aerodyn. 25 (1987) 291–305.

[20] S. Murakami, A. Mochida, Y. Hayashi, Examining the $\kappa$–$\varepsilon$ model by means of a wind tunnel test and large eddy simulation of the turbulence structure around a cube, J. Wind Eng. Ind. Aerodyn. 35 (1990) 87–100.

[21] T. Tamura, K. Kuwahara, Numerical study of aerodynamic behaviour of a square cylinder, J. Wind Eng. Ind. Aerodyn. 33 (1990) 161–170.

[22] W. Frank, Large-eddy simulation of the three-dimensional flow around buildings, Wind Climate in Cities, Kluwer Academic Publishers, Dordrecht, 1995, pp. 669–679.

[23] S. Murakami, Comparisons of various turbulence models applied to a bluff body, J. Wind Eng. Ind. Aerodyn. 46–47 (1993) 21–36.

[24] J.A. Peterka, J.E. Cermak, Adverse wind loading induced by adjacent buildings, J. Struct. Div. Amer. Soc. Civil Eng. 102 (ST3) (1976) 533–548.

[25] L.S. Cochran, J.E. Cermak, Full and model scale cladding pressures on the Texas Tech Experimental Building, J. Wind Eng. Ind. Aerodyn. 41–44 (1992) 1589–1600.

[26] C. Kramer, H.J. Gerhardt, Wind pressures on roofs of very low and very large industrial buildings, J. Wind Eng. Ind. Aerodyn. 38 (1991) 285–295.

[27] K.C. Mehta, M.L. Levitan, R.E. Iverson, J.R. McDonald, Roof corner pressures measured in the field on a low building, J. Wind Eng. Ind. Aerodyn. 41 (1992) 181–192.

[28] H.W. Tieleman, D. Surry, J.X. Lin, Characteristics of mean and fluctuating pressure coefficients under corner (delta-wing) vortices, J. Wind Eng. Ind. Aerodyn. 52 (1994) 263–275.

[29] J.X. Lin, D. Surry, H.W. Tieleman, Wind tunnel experiments of pressures at roof corners of flat roof low buildings, J. Wind Eng. Ind. Aerodyn. 56 (1995) 235–265.

[30] F.H. Proctor, Numerical simulations of an isolated microburst. Part II: Sensitivity experiments, J. Atmos. Sci. 46 (1989) 2143–2165.

[31] R.T. McNider, Investigation of the impact of topographic circulations on the transport and dispersion of air pollutants, Ph.D. Dissertation, University of Virginia, Charlottesville, Virginia, 1981.

[32] R.T. McNider, M.D. Moran, R.A. Pielke, Influence of diurnal and inertial boundary layer oscillations on long-range dispersion, Atmos. Environ. 22 (1988) 2445–2462.

[33] J.L. Eastman, R.A. Pielke, W.A. Lyons, Comparison of lake-breeze model simulations with tracer data, J. Appl. Meteor. 34 (1995) 1398–1418.

[34] M.D. Moran, R.A. Pielke, Evaluation of a mesoscale atmospheric dispersion modeling system with observations from the 1980 Great Plains mesoscale tracer field experiment, Part I: data sets and meteorological simulations, J. Appl. Meteor. 35 (1996) 281–307.

[35] M.D. Moran, R.A. Pielke, Evaluation of a mesoscale atmospheric dispersion modeling system with observations from the 1980 Great Plains mesoscale tracer field experiment, Part II: dispersion simulations, J. Appl. Meteor. 35 (1996) 308–329.

[36] S. Murakami, A. Mochida, Y. Tominaga, Numerical simulation of turbulent diffusion in cities, Wind Climate in Cities, Kluwer Academic Publishers, 1995, pp. 681–701.

[37] R.L. Lee, E. Naslund, Numerical simulations of turbulent dispersion around buildings via a Lagrangian stochastic particle model, 7th Int. Symp. on Measurement and Modeling of Environmental Flows, San Francisco, CA, 1995.