



INVERTED FLOOR WIND-TUNNEL SIMULATION OF STABLY STRATIFIED ATMOSPHERIC BOUNDARY LAYER FLOW

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Abstract—Most of the critical transport processes in the atmosphere are dominated by density stratification; hence, physical modeling facilities which neglect the important contributions of buoyancy are limited to the examination of high winds or those brief moments after sunrise or before sunset when the atmosphere is nominally neutrally stratified. Large new facilities constructed specifically to simulate the atmosphere offer new opportunities to study the physics of mixing processes dominated by stratification. A novel arrangement to simulate stably stratified atmospheric boundary layer flows in large wind tunnels using distributed electrical heaters and an inverted ground plane to simulate nighttime inversions is described, together with initial measurements.

Key word index: Wind tunnel, atmospheric boundary layer, simulation, stable flow.

1. INTRODUCTION

There are at least three succinct reasons physical modeling retains its value in meteorological analysis of stratified flows. First, fluid modeling does some things much better than current analytic and numerical alternatives; e.g. it provides realistic information about surface fluxes, separation, and three-dimensional flow interactions. Second, wind tunnels are in effect analog computers that have the advantage of near-infinitesimal resolution and near-infinite memory. A fluid modeling study employs real fluids, not models of fluids. Hence the fluid model is implicitly non-hydrostatic, non-Boussinesq, compressible and viscous. Third, the fluid model bridges the gap between the fluid mechanician's analytical or numerical models of turbulence and dispersion and their application.‡

Large, thermally stratified wind tunnels currently exist at Colorado State University, U.S.A. (2 m × 2 m cross-section, 30 m long) and at the National Institute for Environmental Studies, Japan (2 m × 3 m cross-section, 24 m long). New wind-tunnel facilities specifically designed to study stratified flows are under construction or evaluation at National Power, Leatherhead, U.K. (1.5 × 3.5 m cross-section, 20 m long), the Ecole Centrale de Lyon, France (2 × 3.7 m cross-section, 15 m long), Karlsruhe University, Germany (0.5 m × 1 m cross-section, 4 m long), and the new facility at Monash University, Australia (5 m × 10 m cross-section, 40 m long). Doubtless other configurations also exist. At this time, few results have been published based on experiments performed in

these new facilities. This paper examines stratified wind-tunnel data generated in the new large Monash Environmental Wind-tunnel (EWT) facility which is suitable for extended wind-engineering applications.

2. SIMULATION CRITERIA

Simulation of atmospheric motions by wind-tunnel flows has occurred for almost 100 years since Professor LeCour constructed a windmill test facility in Askov, Denmark, in 1895 and Gustaf Eiffel designed his exhibition tower in 1889. Background reviews about laboratory simulation were prepared by Cermak (1975), Davenport and Isyumov (1968) and Melbourne (1977). Meroney (1981) considered the simulation of complex terrain and valley drainage situations. Snyder (1981) suggested similarity criteria for the study of air-pollution meteorology in near neutral situations. Meroney (1987) extended the discussion to the simulation of dense gas plumes in the surface layer. Meroney *et al.* (1975) and Avissar *et al.* (1990) proposed simulation criteria and operating ranges for the simulation of sea and land breezes. Meroney (1990) provides an extended discussion of modeling limitations, similarity considerations, facilities, and insights obtained from specific studies of both neutral and stratified flow over complex terrain.

During physical model simulations of atmospheric flows, scale-model replicas of observed ground-level buildings and terrain are constructed and inserted into a laboratory flow facility. The flow characteristics and stratifications of the air in the wind tunnel are adjusted to be as similar as possible to the atmospheric conditions. Complete equivalence of the laboratory model

‡ Reworded from Snyder (1981).

and atmospheric prototype flow fields requires geometric, kinematic, dynamic, and thermal similarity. In addition, boundary conditions upstream, downstream, at the lower surface, and near the top of the physical model must be similar to those at the corresponding boundaries of the modeled atmospheric domain. These multiple similarity requirements, the characteristics of the wind tunnel and its instrumentation, and the nature of the atmospheric phenomenon to be modeled all help to determine the operating range (OR) for a wind-tunnel simulation.

Similarity characterization of stratified atmospheric flows are reviewed by Avissar *et al.* (1990) and Meroney and Melbourne (1992). Equality of these similitude parameters must be supplemented by the requirements that the surface boundary conditions and the approach-flow characteristics also be similar for model and prototype. If all of the above conditions are met simultaneously, then all scales of motion ranging from the atmospheric microscale to mesoscale could be simulated exactly by the laboratory model. Unfortunately, not all conditions can be satisfied simultaneously by a scaled model since some are incompatible or conflicting; hence, only partial or approximate similarity can be achieved. This suggests that a laboratory model for a particular meteorological situation must be designed to simulate most accurately those scales of motion which are of greatest significance for the application.

Simulation of stably stratified atmospheric boundary layers requires geometric similarity of surface roughness, dynamic similarity of inertial and buoyancy forces, and similarly distributed mean and turbulent upwind velocity and temperature profiles. Viscous and Coriolis forces are not expected to dominate; hence, equivalence of model and prototype Rossby and Reynolds numbers are not required. For these experiments, equivalence between approach flow bulk Richardson numbers, $Ri_B = [g(\Delta T/T)\Delta z/(\Delta U)^2]$, is desired, where ΔT and ΔU are differential changes in mean temperature and velocity over some incremental reference height in the atmospheric surface layer, Δz . The inverse of the absolute temperature, $1/T$, reflects the influence of atmospheric compressibility on buoyancy.

Approach flow conditions to Pasquill categories E and F ($Ri_B = 0.014$ – 0.062 and 0.062 – 0.090 or $L_{mo} = 23$ – 125 m and 13 – 23 m, respectively) were sought. It is possible to estimate the near-surface temperature gradients required to model E and F stability for different tunnel wind speeds based on Richardson number equality (Golder, 1972), where

$$Ri = \frac{g(T_H - T_B)(H - B)}{T(U_H - U_B)^2}$$

and H is the upper sensor height and B is the lower sensor height. For a 1:600 scale model a prototype 3.5 m s^{-1} speed at a height of 22 m over a surface roughness of 0.05 m and a selected model wind speed

of 0.5 m s^{-1} at a model height of 37 mm would require a model temperature difference $\Delta T = 3$ – 13°C over a 35 mm height for Pasquill Category E conditions and a model temperature difference $\Delta T = 13$ – 19°C over the same height for Pasquill Category F conditions.

3. EXPERIMENTAL TECHNIQUES TO MODEL STABLY STRATIFIED SITUATIONS

Conventionally, stable stratification in wind tunnels is simulated using cold tunnel floors and heated air. Such a configuration requires either floor refrigeration or the use of cryogenic temperature gases such as liquefied air or sublimated CO_2 from dry ice. Since the experiments were to be performed over a large model in the Monash Environmental Wind Tunnel (MEWT: 10 m wide \times 5 m high \times 40 m long), an inverted model arrangement was chosen, and all heating was provided by electrical resistors placed along a false wind-tunnel roof. Britter (1974) used a similar arrangement of roof-mounted heaters to study turbulence development in a density stratified boundary layer.

A false ceiling 18 m long \times 6 m wide was constructed to insert in the MEWT, Fig. 1. The movable side walls of the Monash facility were adjusted to a 6 m width. The ceiling was made modularly from five $3.6 \text{ m} \times 6 \text{ m}$ plates and placed 2.5 m above the tunnel floor. The lower surface of the false roof was covered with aluminum foil-wrapped insulation to reduce heat loss and thermal inertia. All joints between the five plates were taped to smooth intersections to remove leaks.

Heating to produce the stably stratified boundary layer was produced by 24 electrical heater elements, Fig. 2. Each element was individually rated to 2 kW for a 240 V potential, but were connected in various serial and parallel combinations. Twelve elements were placed in a vertical grid just downwind of the roof entrance, and 12 more elements were distributed downwind in four rows next to the roof to act as booster heaters. At the low velocities used (0.5 m s^{-1}) dissipation of about 9 kW occurred. This energy sufficed to heat a boundary layer 300 mm thick, which is from 5 to 10 times the depth of the anticipated model-scale Monin–Obukhov stability length, $L_{mo} = 30$ – 60 mm. Once the wind speed and heater elements were turned on it took from 1 to 2 h for the flow conditions to stabilize.

The low air velocities and high temperature differences required that special instrumentation be utilized to assure that measurements were not biased by radiation errors. Velocities were measured using a Thermal Systems Inc. (TSI) Model 1650 temperature corrected hot-film anemometer. The measurement element was placed horizontal and perpendicular to the flow and moved vertically on a mobile traverse stand. From 10 to 20 measurements were made at vertical stations located from 10 to 860 mm from the ceiling.

Temperatures were measured using an array of 10 shielded thermistor probes. Two probe arrays were placed on mobile traverse stands, which could be located beneath the selected measurement stations. Measurements were also made at locations from 10 to 860 mm from the ceiling. The shielded system was calibrated against aspirated heated air, and the thermistors were found to be accurate within $\pm 0.5^\circ\text{C}$.

4. EXPERIMENTAL RESULTS

Flow visualization revealed that air flow over the inverted surface ranged from fully turbulent to strongly stable. Single traverses of temperature were made 9 m downwind from the beginning of the false

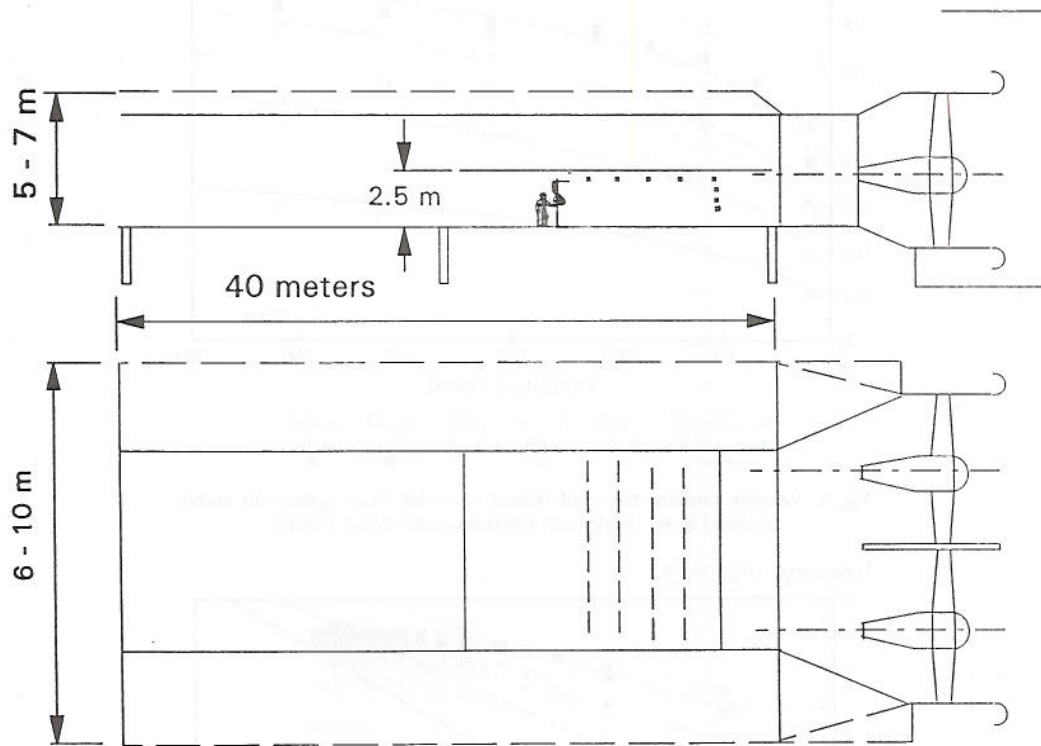


Fig. 1. Inverted ceiling system installed in Monash Environmental Wind Tunnel to simulate stably stratified atmospheric boundary layers.

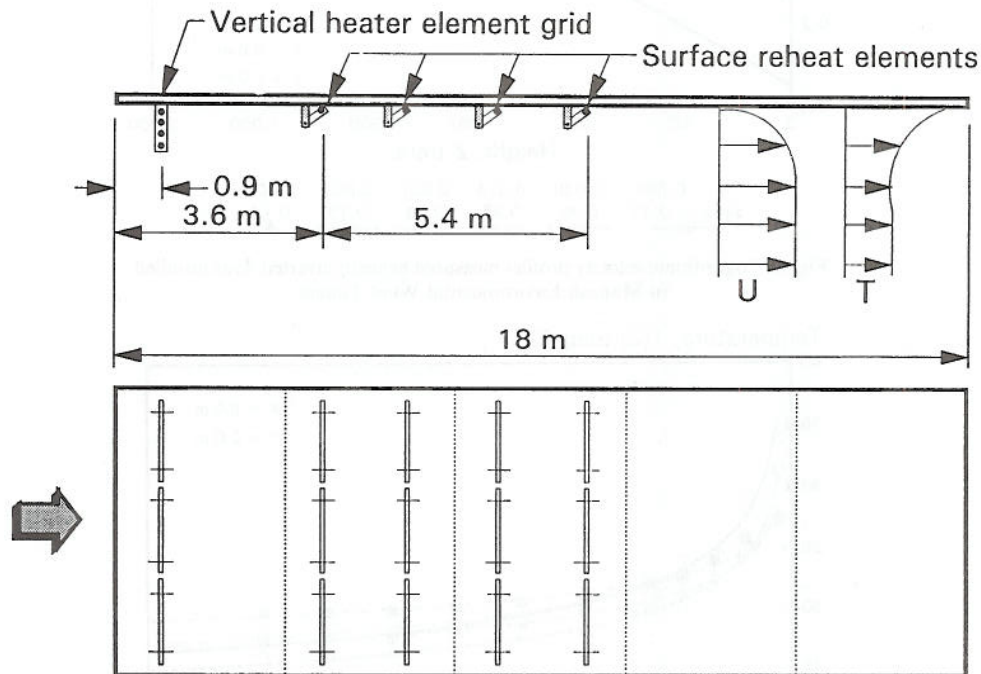


Fig. 2. Heater element installation configuration for inverted floor as installed in Monash Environmental Wind Tunnel.

ceiling for a sequence of six different wind speeds ranging from 0.6 to 1.5 m s^{-1} . Measured velocity and temperature profiles are displayed in Figs 3 and 5, respectively. Examination of semi-logarithmic plots

of the velocity distribution reveals that the effective surface drag coefficient and surface roughness for the neutral condition were $u_* / U_{\infty} = 0.040$ and $Z_0 = 0.020 \text{ mm}$. Log-log plots of the same distributions

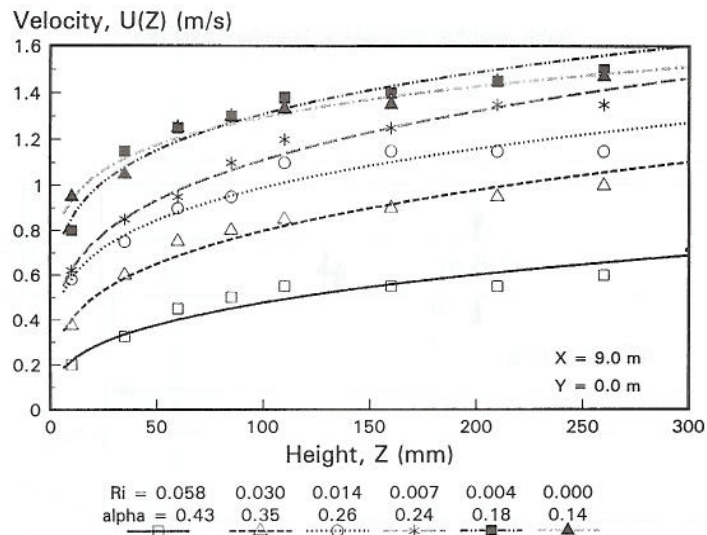


Fig. 3. Velocity profiles measured beneath inverted floor system for stably stratified flows in Monash Environmental Wind Tunnel.

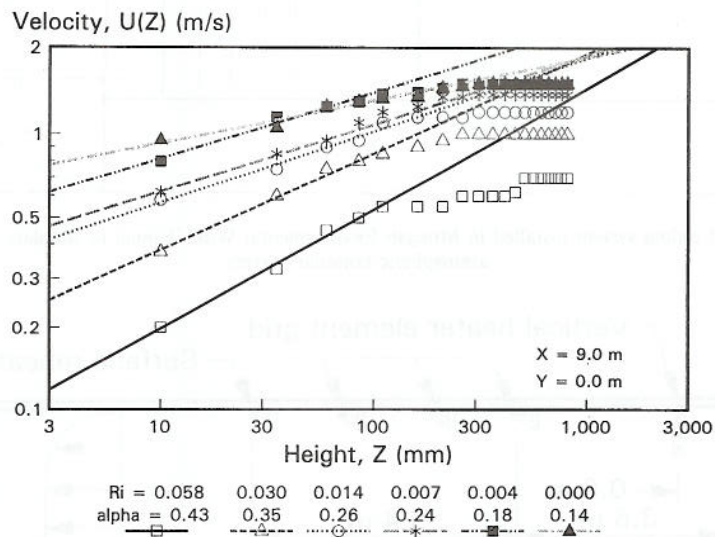


Fig. 4. Logarithmic velocity profiles measured beneath inverted floor installed in Monash Environmental Wind Tunnel.

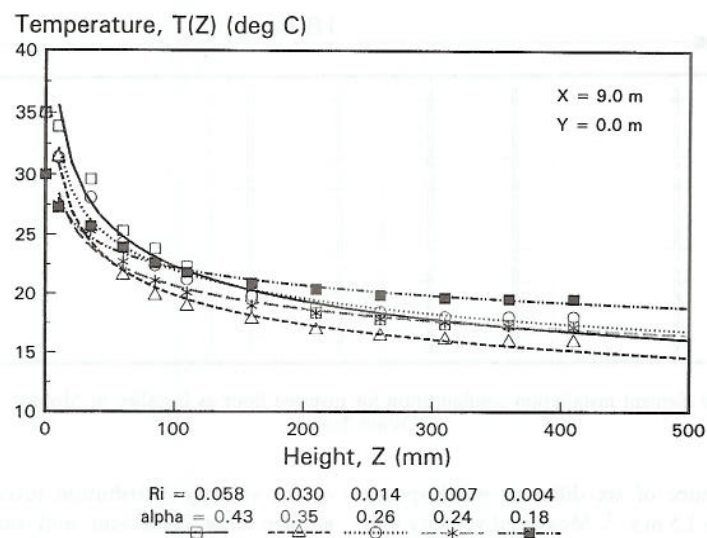


Fig. 5. Temperature profiles measured beneath inverted floor system for stably stratified flows in Monash Environmental Wind Tunnel.

Table 1. Model/prototype conditions for stably stratified flows

Prototype conditions								
PG stability condition	Pro wind speed (ms ⁻¹)	Monin-Obukhov* length, L _{mo} (m)	Z _o (m)	H (m)	B (m)	(Ri) _B	(T _H -T _B) (K)	Alpha (Huang, 1981)
D _{min}	5.0	-150	0.01	21	1	-0.006	-0.23	—
D	5.0	1.0E+06	0.01	21	1	0.000	0.00	0.14
D	5.0	280	0.01	21	1	0.004	0.14	0.17
D	5.0	160	0.01	21	1	0.007	0.25	0.18
D _{max} -E _{min}	3.5	125	0.01	21	1	0.009	0.16	0.19
E	3.5	80	0.01	21	1	0.014	0.25	0.23
E	3.5	36	0.01	21	1	0.030	0.54	0.30
E _{max} -F _{min}	3.5	23	0.01	21	1	0.045	0.81	0.35
F	3.5	17	0.01	21	1	0.058	1.03	0.39
F _{max}	3.5	13	0.01	21	1	0.070	1.25	0.44

*Average L_{mo} taken from Golder (1972), Fig. 4, for PG category and Z_o estimated for short grass covered terrain.

Model condition									
Length scale ratio: 600									
PG stability condition	Wt wind speed (ms ⁻¹) (measured)	Monin-Obukhov* length (mm) (implied)	Z _o (mm) (measured)	H (mm) (measured)	B (mm) (measured)	(Ri) _B (measured)	(T _H -T _B) (K) (predicted)	(T _H -T _B) (K) (measured)	Alpha (measured)
D _{min}	1.00	-250.0	0.02	35.0	1.7	-0.006	-0.01	—	—
D	1.00	1.0E+06	0.02	35.0	1.7	0.000	0.00	0.00	0.14
D	1.15	466.7	0.02	35.0	1.7	0.004	4.58	2.70	0.18
D	0.85	266.7	0.02	35.0	1.7	0.007	4.41	2.40	0.24
D _{max} -E _{min}	0.75	208.3	0.02	35.0	1.7	0.009	4.40	—	—
E	0.75	133.3	0.02	35.0	1.7	0.014	6.90	3.60	0.26
E	0.60	60.0	0.02	35.0	1.7	0.030	9.57	3.60	0.35
E _{max} -F _{min}	0.33	38.3	0.02	35.0	1.7	0.045	4.18	—	—
F	0.33	28.0	0.02	35.0	1.7	0.058	5.33	5.40	0.43
F _{max}	0.33	21.7	0.02	35.0	1.7	0.070	6.48	—	—

*Average L_{mo} taken from Golder (1972), Fig. 4, for PG category and Z_o estimated for short grass covered terrain.

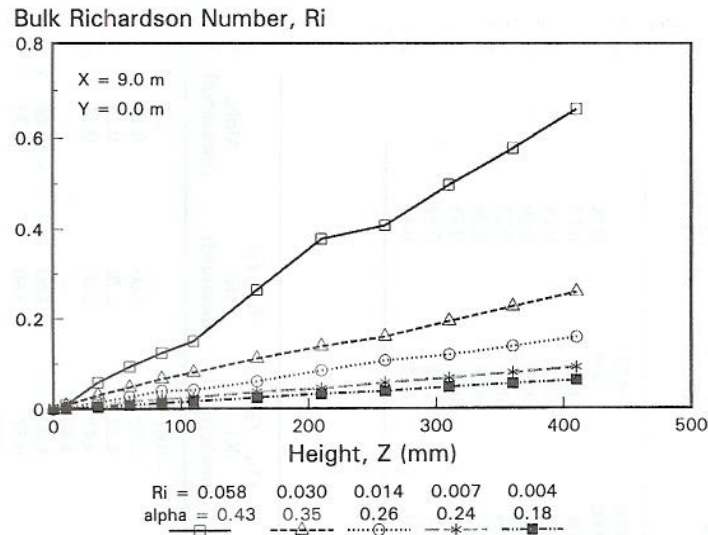


Fig. 6. Bulk Richardson number profiles measured beneath inverted floor system for stably stratified flows in Monash Environmental Wind Tunnel.

provide information about velocity profile power-law exponents, α , vs stratification, Fig. 4 and Table 1. The measured bulk Richardson numbers and power-law exponents are consistent with data recorded at full scale (Table 1) and permit the specification of equivalent Monin–Obukhov stability length parameters for a scale of 1:600, see Fig. 6.

Correlations between measured and analytically predicted field values for stratified flows are noted in Table 1. Prototype relations between Pasquill–Gifford category, Richardson number and Monin–Obukhov length are calculated using the tables of Golder (1972) and the Lagrangian similarity expressions for dimensionless shear and wall profiles as noted in Meroney (1986). Prototype values for the velocity profile power-law exponents at different stably stratified conditions were extracted from Huang (1979).

Model conditions are implied by the requirement for equivalence of similarity parameters (H/L_{mo} or Ri_B). Of course, each Pasquill–Gifford stability condition designation corresponds to a range in the more quantitative similarity parameters H/L_{mo} or Ri_B . Also, there are many combinations of model velocity and model temperature profiles which can produce equivalent magnitudes of the similarity parameters. Given only mean flow information a physical modeler searches for equivalence between prototype and model Ri_B anticipated and measured temperature variations ($T_H - T_B$), and velocity power law exponents, α . Comparison of the prototype and model conditions displayed in Table 1 suggest that the inverted floor technique reproduced bulk Richardson number variations between 0.000 and 0.058. The method produced model temperature differences ranging from 0.00 to 5.40 when a range from 0.00 to 9.57 might be anticipated. Finally, the measured model velocity profile

power law exponents ranged from 0.14 to 0.43 whereas prototype values ranged from 0.14 to 0.44.

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REFERENCES

- Avissar R., Moran M.D., Wu G., Meroney R. N. and Pielke R.A. (1990) Operating ranges of mesoscale numerical models and meteorological wind tunnels for the simulation of sea and land breezes. *Boundary-Layer Met.* **50**, 227–275.
- Britter R. E. (1974) An experiment on turbulence in a density stratified fluid. Ph.D. thesis, Department of Mechanical Engineering, Monash University, Clayton, Victoria, Australia.
- Cermak J. E. (1975) Applications of fluid mechanics to wind engineering—a Freeman scholar lecture. *J. Fluids Engng* **97**, 9–38.
- Davenport A. and Isyumov N. (1968) The application of the boundary layer wind tunnel to the prediction of wind loading. *Proc. Int. Research Seminar on Wind Effects on Buildings and Structures*, 11–15 September 1967, Ottawa, Canada. University of Toronto Press, Toronto, Canada.
- Golder D. G. (1972) Relations among stability parameters in the surface layer. *Boundary-Layer Met.* **3**, 47–58.
- Huang C. H. (1979) A theory of dispersion in turbulent shear flow. *Atmospheric Environment* **13**, 453–463.
- Melbourne W. H. (1977) Development of natural wind models at Monash University. *6th Australian Hydraulics and Fluid Mechanics Conference, Adelaide, Australia*, pp. 190–194. The Institution of Engineers, Australia, National Conference Publication No. 77/12.
- Meroney R. N. (1981) Physical simulation of dispersion in complex terrain and valley drainage flow situations. In *Air Pollution Modeling and Its Application* (edited by De Wispelaere C.). Plenum Publishing Co., New York.

- Meroney R. N. (1986) Guideline for fluid modeling of liquefied natural gas cloud dispersion, volume II: Technical Support Document. Gas Research Institute Technical Report No. GRI 86/0102.2, 269 pp.
- Meroney R. N. (1987) Guidelines for fluid modeling of dense gas cloud dispersion. *J. hazard. Mater.* **17**, 23–46.
- Meroney R. N. (1990) Fluid dynamics of flow over hills/mountains—insights obtained through physical modeling. In *Atmospheric Processes Over Complex Terrain* (edited by Blumen W.), Chapter 7, pp. 145–171. American Meteorological Society Monograph No. 45, Boston.
- Meroney R. N. and Melbourne W. H. (1992) Operating ranges of meteorological wind tunnels for the simulation of convective boundary layer phenomena. *Boundary-Layer Met.* **61**, 145–174.
- Meroney R. N., Cermak J. E. and Yang B. T. (1975) Modeling of atmospheric transport and fumigation at shoreline sites. *Boundary-Layer Met.* **9**, 69–90.
- Snyder W. H. (1981) Guideline for fluid modeling of atmospheric diffusion. U.S. Environmental Protection Agency Report EPA-600/8-81-009, 185 pp.

