D

DRAFT VERSION
RNM - Jan 89

CHAPTER 6

FLUID DYNAMICS OF FLOW OVER HILLS/MOUNTAINS INSIGHTS OBTAINED THROUGH PHYSICAL MODELING

Robert N. Meroney

TABLE OF CONTENTS

1. Introduction 1
   1.1. Advantages and disadvantages of fluid modeling 2
   1.2. Historical perspectives 3

2. Similarity considerations 5
   2.1. Similitude parameters 7
   2.2. Partial simulation of complex terrain flows 8
   2.3. Performance envelopes for fluid modeling 12

3. Facilities for fluid modeling of complex terrain meteorology . . . 16
   3.1. Wind tunnels 17
   3.2. Drainage flow facilities 18
   3.3. Water channels and rotating tanks 19
   3.4. Instrumentation 19

4. Neutral flow over hills, ramps and escarpments 20
   4.1. Idealized two-dimensional terrain flow studies 21
   4.2. Idealized three-dimensional terrain flow studies . . . 27
   4.3. Field/laboratory comparisons 30
   4.4. Conclusions from neutral airflow terrain studies . . . 35

5. Stratified flow over hills and ramps 36
   5.1. Idealized two-dimensional flow domains for waves and blocking 36
   5.2. Downslope winds, valley fLows induced by cross-winds . 37
   5.3. Idealized three-dimensional terrain studies 38
   5.4. Field/laboratory comparisons 40
   5.5. Conclusions from stratified airflow terrain studies . . 41

6. Drainage flow phenomena 42

7. Diffusion phenomena in complex terrain 43

8. Summary 45

LIST OF TABLES

Table I	Typical boundary-layer wind tunnel characteritistics	47
Table II	Typical wind tunnel and field parameter ranges	48

LIST OF FIGURES

Figure 1 Performance envelope for physical modeling of shear flows over complex terrain in a typical boundary-layer wind tunnel . . . 49
Figure 2 Performance envelope for physic l modeling of stratified shear flows over complex terrain in a typical boundary-layer wind tunnel 49
Figure 3 Open circuit meteorological wind tunnel (Fluid Dynamics and Diffusion Laboratory, Colorado State University) 50
Figure 4 Alternative methods for generating boundary layer flows in a meteorological wind tunnel (Plate, 1982) 50
Figure 5 Closed circuit meteorological wind tunnel with stratification (Fluid Dynamics and Diffusion Laboratory, Colorado State University) 51
Figure 6 Ducted thermally stratified boundary layer wind tunnel (Rau and Plate, 1986) 51
Figure 7 Large stratified water channel/towing tank (Environmental Protection Agency, Raleigh, NC) 52
Figure 8 Water channel traverse with lighting and photographic arrangement for dye visualization during two tank experiments (Hunt *et al.*, 1978) 52
Figure 9 Hydrogen bubble apparatus for flow visualization in water channels 53
Figure 10 Details of a smoke-wire probe used to obtain airflow velocities for barostromatic model airflow (Orgill *et al.*, 1971a) 53
Figure 11 Laboratory experimental arrangement for obtaining airflow velocity measurements by the stereo two-camera smoke-wire method (Orgill *et al.*, 1971a) 54
Figure 12 Methods in which terrain features affect atmospheric motions (Drake *et al.*, 1977) 54
Figure 13 Contours of flow characteristics over a triangular ridge, h/L = 1/6 (Meroney *et al.*, 1978b) 55
Figure 14 Contours of flow characteristics over a triangular ridge, h/L = 1/2 (Meroney *et al.*, 1978b) 55
Figure 15 Mean velocity profiles downwind of a triangluar hill $h/L_u = 0.5$ and $h/L_d = 1, 0.33, 0.25, 0.17$ (Bouwmeester *et al.*, 1978) . . 56
Figure 16 Velocity speedup between approach flow and crest over different hill shapes (Rider and Sandborn, 1977) 57
Figure 17 Comparison between wind tunnel (w.t.) and numerical simulation (n.s.) of velocities over a 1:4 sinusoidal hill. L is half width of hill. (Derickson and Meroney, 1977) 57
Figure 18 Schematic of the vortex containing wake produced by a hemisphere (Hansen and Cermak, 1975) 58
Figure 19 Horizontal isotachs, contoured model with tree shelterbelts at a height of 10m (Meroney *et al.*, 1978) 58
Figure 20 Vertical section of isotachs over Rakaia Gorge contoured model with shelterbelts (Meroney *et al.*, 1978a) 59

Figure 21 Vertical section of isoturbs over contoured Rakaia Gorge model with shelterbelts (Meroney *et al.*, 1978a) 59
Figure 22 Vertical profiles of mean speed and speedup at the hilltop location for two wind directions in wind-tunnel and full-scale flows. (Teunissen *et al.*, 1987) 60
Figure 23 Vertical profiles of σ_u and $\Delta\sigma_u$ at the hill top (HT) and reference location (RS) in wind-tunnel and full-scale flows for $\phi = 235°$. (Teunissen *et al.*, 1987) 60
Figure 24 Domains of stratified flow behavior over surface-mounted obstacles as a function of flow-depth Froude number and obstacle to depth ratio 61
Figure 25 Schematic arrangement of baffles in a water filled towing tank to simulate an infinite depth flow (Baines and Hoinka, 1985) 61
Figure 26 Criteria for the presence of columnar upstream motion and upstream blocking in terms of Nh/U for a range of surface mounted obstacle shapes. Hatched regions denote error bars. (Baines and Hoinka, 1985) 62
Figure 27 Sketch of stably stratified flow over two humps where the surface height is equivalent to the sum of their separate heights, two spacings (Tampieri and Hunt, 1984) 62
Figure 28 Water channel experiments performed with obstacles 1 cm high. Full symbols correspond to good penetration; open symbols to no penetration; half-filled symbols to inter-mediate cases (Tampieri and Hunt, 1984) 63
Figure 29 Schematic of dividing-streamline concept for stratified flow over hills (Hunt and Snyder, 1980) 63
Figure 30 Angle sensitivity of lateral movement around a hill in stratified flow (Snyder, 1988) 64
Figure 31 Dye streaks obtained during stratified tow-tank experiments of flow over triangular-shaped ridges of various aspect ratio (Castro *et al.*, 1983) 64
Figure 32 Schematic representation of the wind tunnel airflow from the combination of windtunnel and dry ice (Orgill *et al.*, 1971a) 65
Figure 33 Comparison between the vertical rise of model and field tracer plumes during the Eagle Valley/Climax cloud seeding experiments (Orgill *et al.*, 1971a) 65
Figure 34 Schematic of convection chamber at Colorado State University used to simulate moutain-valley drainage patterns 66
Figure 35 Velocity and temperature profiles taken over the mine site for the Coal Creek drainage flow tests; Ri = 1.69 (Petersen and Cermak, 1980) 66
Figure 36 Maximum ground level concentrations versus downwind distance with and without model terrain for a 6.7 m/s prototype wind speed and Kingston Power Plant Units 1 through 9 operating (Graham *et al.*, 1978) 67

Figure 37 Plume visualization of side view of plume dispersion from a lead smelter in Glover, MO. Simulation in a stratified towing tank for neutral and stratified flows (Liu and Lin (1975) . 67
Figure 38 Plume visualization of top view of plume dispersion from a lead smelter in Glover, MO. Simulation in a stratified towing tank for neutral and stratified flows (Liu and Lin (1975) . . 68
Figure 39 Laboratory and field data from Glover lead smelter plume simulation compared with field data of plume rise in calm and stable flows (Liu and Lin, 1975) 68

CHAPTER 6

FLUID DYNAMICS OF FLOW OVER HILLS/MOUNTAINS INSIGHTS OBTAINED THROUGH PHYSICAL MODELING

Robert N. Meroney[1]

ABSTRACT

This chapter will consider the advantages and limitations of physical modeling, review the principle conclusions drawn through physical modeling, and suggest experiments that might result in a better understanding of the flow processes over complex terrain.

1. Introduction

Meteorologists are frequently faced with problems requiring quantitative estimates of air flow patterns and turbulence characteristics over complex terrain. Use of the wind flow information includes air pollution zoning, prediction of smoke movement from forest fires or slash burning, mine tailing dust dispersal, estimation of the movement of vegetative disease vectors or pests, and the siting of fossil fuel burning industrial facilities or power plants. In view of the practical difficulties in obtaining useful results, whether by analytical, numerical or field investigation means, it is natural to explore the possibilities of simulating flow and diffusion over irregular terrain by means of physical model experiments on the laboratory scale.[2]

---

[1] Professor, Fluid Mechanics and Wind Engineering, Director, Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, Colorado.

[2] Sometimes also called "fluid" modeling or "hydraulic" modeling.

Successful modeling of some of the more complex atmospheric surface layer phenomena in wind tunnels and water channels date back over fifty years. Although guidelines for modeling flow over complex terrain are essentially similar to those for modeling around buildings and obstacles, a few unique features are reviewed here briefly; characteristics of neutral flow over hills, ramps and escarpments are discussed; and deductions from stratified and drainage flow experiments are noted. Principle conclusions drawn through physical modeling are summarized, and experiments that might result in a better understanding of the flow processes over complex terrain are proposed.

1.1. Advantages and disadvantages of fluid modeling

There are three succinct reasons why physical modeling retains its value in meteorological analysis of terrain flows. First, fluid modeling does some things much better than current analytic and numerical alternatives. For example fluid modeling provides realistic sub-grid scale information about surface fluxes, separation, and three-dimensional flow interactions. Secondly, wind tunnels are, in effect, analog computers which 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-Boussinesqu, compressible, and it includes variable fluid properties, non-slip boundary conditions, and dissipation. Real fluids permit flow separation and recirculation. All conservation equations are automatically included in their correct form in a laboratory model without truncation or differencing errors, and there are no missing terms or approximations. Third, the fluid model bridges the gap between the fluid mechanician's analytic or numeric models of turbulence and dispersion and their application. Fluid modeling may be used to plan field experiments, to provide conservative estimates of transport, and to validate modules of numerical code.

The most serious limitations of physical modeling are normally related to fluid model facility size. Limitations of facility size can introduce errors associated with wall reflections, side wall boundary layers, and low Reynolds number viscous distortions. Turbulence scaling also reduces the span of the inertial sub-range of eddies. Large weather-size turbulence eddies and the diurnal cycle are absent during physical model experiments, since current facilities do not include non-stationary aspects of atmospheric motion. Only recently have some facilities produced useful elevated inversions or convective boundary layers.

1.2. Historical perspectives

Physical modeling studies of atmospheric flow over complex topography span some 60 years and research in more than seven countries. Early work at the National Physical Laboratory, UK, by Field and Warden (1929-30) led to the evaluation of air currents around the Rock of Gibraltar for airfield safety. The wind field up to 7000 feet high over a 1:5000 scale model of the Gibraltar peninsula was mapped using visualization flags and thread streamers. Subsequent measurement of the actual flows around the Rock of Gibraltar with pilot balloons and kites found that the model "closely forecast what occurred in nature at Gibraltar, in regard to wind directions and the distribution of vortices and vertical currents."

About the same time Abe (1929) used cold CO_2 sublimated from dry-ice flowing over a 1:50,000 scale model of Mt. Fuji, Japan, to study mountain wave clouds. Visualization photographs revealed wave like motions near the mountain peak which correspond with the presence of laminar wave clouds over the actual volcano.

Theodore von Karman consulted on wind tunnel studies of flow over a number of mountainous areas in New England at scales ranging from 1:5000 to 1:8000 to identify good wind power sites (Putnam, 1948). Unfortunately, the researchers failed to consider the effects of the surface shear layer; hence, the results failed to agree with field measurements. Later English wind-energy researchers estimated wind speeds over terrain by measuring voltage potential variations over a conductive model in an electrolytic tank (Golding, 1955). The method presumed airflow over complex terrain was inviscid potential flow and streamlines obeyed only the Laplace equation.

During the 1950s Robert Long initiated an extensive series of channel flow experiments to investigate stratified flows over mountainous terrain (1954, 1959). During his experiments Long towed two-dimensional models of various mountain shapes over stratified brine solutions divided into two or more layers. These experiments successfully reproduced many of the features of mountain lee-wave structure, and the data provided verification for a variety of linear lee-wave models. Subsequent tests by many researchers have focused on improving and varying the stratification, removing the influence of wave reflections, and adding three-dimensional models.

These and other experiments laid the foundations for the new field of Wind Engineering. Requirements for simulation of atmospheric motions and the development of meteorological laboratory facilities were subjects of intense study during the period from 1950 to 1970. Modifications to conventional aeronautical wind tunnels to enable simulation of neutral and thermally stratified boundary layers were proposed by Strom (1952), Jensen (1958), Cermak (1958), and Counihan (1969). Cermak *et al.* (1966) developed similarity criteria for simulation of the atmospheric boundary layer based on the development of thick thermally-stratified boundary layers. Orgill (1971) used barastromatic simulation criteria to predict transport and diffusion of ground-based cloud seeding generators over mountainous terrain. Snyder (1972, 1981) critically evaluated the advantages and limitations of physical modeling when simulating atmospheric transport over irregular terrain. Meroney (1986) extended the simulation discussion to the motion of dense gas clouds over irregular terrain.

2. Similarity considerations

The concept of similitude is basically simple. Two systems at different geometric scales will exhibit similitude if a one to one correspondence exists in space and time between fluid particle kinematics (locations, velocities, accelerations and rotations) caused by fluid particle dynamics (pressures, gravity, viscous forces, *etc.*), when properly scaled by characteristic scales of fluid properties, force, length and time. To achieve this similarity, however, is not trivial. The specification of dimensionless parameters which guarantee similarity has historically been the subject of much discussion and debate.

In the nineteenth century a number of workers (most notably Lord Rayleigh) commonly solved problems by direct use of the similarity principle with the intuitive identification of relevant force ratios. During the twentieth century, the force ratio methods lost favor and were replaced almost entirely by dimensional analysis, as represented by the Buckingham Pi Theorem. A number of authors including Cermak (1975), McVehil *et al.* (1967), Bernstein (1965), and Snyder (1972) derived the governing parameters for atmospheric heat, mass, or momentum transport by dimensional analysis, normalization, and inspectional analysis. Another group justify similitude by considerations of turbulence theory and recent reviews of full scale wind data which present the characteristics of the prototype atmospheric wind on a parametric basis (Nemoto ,1961, 1962; Counihan, 1969, 1975; Cook, 1977; and Melbourne, 1977). Although all investigators do not agree concerning details, most would concur that the dominant mechanisms can now be identified and are understandable.

For complete flow similarity in two systems of different length scales, geometrical, kinematical, dynamical and thermal similarity must be achieved. In addition, boundary conditions upstream, in the upper atmosphere, and downstream should also be similar.

Geometrical similitude exists between model and prototype if the ratios of all corresponding dimensions in model and prototype are equal. This is realized by using an undistorted scale model of the prototype geometry. Kinematic similitude exists between model and prototype if the paths of homologous moving particles are geometrically similar and if the ratio of the velocities of homologous particles are equal. Dynamic similitude exists between geometrically and kinematically similar systems if the ratios of all homologous forces in model and prototype are the same. Thermal similitude exists if the temperature or density stratification are similar.

2.1. Similitude parameters

The proper similitude parameters governing the phenomena of interest may be established by dimensional analysis, similarity theory or inspectional analysis. Good descriptions of these methods are available in various textbooks and publications (*e.g.*, Kline, 1965; Meroney *et al.*, 1978; Meroney, 1986). The pertinent parameters for transient, turbulent airflows are:

$Ro = U(L\Omega)^{-1}$, the Rossby number,

$Eu = \Delta P(\rho U^2)^{-1}$, the Euler number,

$Re = \rho UL\mu^{-1}$, the Reynolds number,

$Ri = gL\Delta T(TU^2)$, the Richardson number,

$Pe = \rho CpULk^{-1}$, the Peclet number,

$Pr = \mu Cpk^{-1}$, the Prandtl number,

$Sc = \mu(\rho D)^{-1}$, the Schmidt number, and

$Ec = U^2(Cp\Delta T)^{-1}$, the Eckert number.

"Exact" similitude requires equality of the nondimensional coefficients listed above for the physical model and the prototype situation. If separate length scales are chosen for the different coordinate directions additional parameters are generated; however, current wisdom is that distorted geometric scaling is not normally justified (Robins and Hertig, 1986).

Furthermore boundary conditions governing the flow domain of interest must be similar for the model and prototype. Boundary conditions would require similarity of the following features:

<u>Surface boundary conditions</u>

a. Topographic relief,
b. Surface roughness distribution,
c. Surface temperature distribution, and
d. Reproduction of the shapes and sizes of associated obstacles, buildings, fences, *etc*.

<u>Approach-flow boundary conditions</u>

a. Distributions of mean and turbulent velocities,
b. Distributions of mean and fluctuating temperatures and humidities, and
c. Distribution of turbulent scales and energies.

<u>Aloft boundary conditions</u>

a. The upper streamline should follow a similar trajectory with respect to the ground surface, and
b. The longitudinal pressure gradient should be nearly zero.

2.2. Partial simulation of complex terrain flows

The seven governing equations used to specify the parameters above and their associated boundary conditions contain seven unknowns, U_i, T, p, ρ, and X, so that (in principle) their solutions can be determined. If all the foregoing requirements were met simultaneously, all scales of motion ranging from micro to mesoscale, 10^{-1} to 10^5 m, could be simulated within the model flowfield. However, all of the requirements cannot be satisfied simultaneously by existing laboratory facilities, and "partial" or "approximate" simulation must be used. This limitation requires that atmospheric simulation for a particular geophysical application must be designed to simulate most accurately those scales of motion which are of greatest significance for that application. By considering each similarity requirement separately it is possible to determine for what flow features "exact" similarity between the laboratory and the atmospheric boundary layer is lacking.

The effects of equal Rossby numbers cannot be obtained in non-rotating wind tunnels or channels. The Rossby number is a measure of the relative magnitudes of the advective or local accelerations resulting from unsteadiness or divergence in the flow field and the Coriolis accelerations associated with the earth's rotation. The Ekman spiral in the Earth's wind profile results from such Coriolis accelerations. The laboratory boundary layer is an adequate model for atmospheric flow when time scales or transport distances are not too large. Atmospheric measurements made over complex mountainous terrain rarely indicate the presence of an Ekman spiral. Laboratory simulations of complex terrain fetch distances from 10 to 20 km have compared reasonably well with field observations. For example, Meroney *et al.* (1978) observed that the Rakaia Gorge, New Zealand, area has a characteristic length of 20 km, northwesterly winds are at least 20 m sec^{-1} at gradient wind height, and $\Omega = 9 \times 10^{-5}$ sec^{-1} at $\phi = 40$ degree latitude; hence, Ro = 11, ie., the inertial effects are an order of magnitude greater than the Coriolis accelerations. Indeed Hoxit (1973) and Scorer (1978) observe that most of the time the air is not actually in equilibrium with Coriolis forces due to thermal wind effects.

The Euler number compares the relative magnitude of pressure fluctuations and inertial accelerations. This parameter is usually of order one and is automatically simulated.

Equal <u>Reynolds numbers</u> are not attainable (except in pressurized or cryogenic gas tunnels). However, this does not seriously limit capabilities for modeling the atmospheric boundary layer over irregular terrain at high wind speeds, since the significant flow characteristics are but weakly dependent on Reynolds number. Townsend (1956) suggested turbulence structure will be similar at all sufficiently high Reynolds numbers. This hypothesis of Reynolds number independence is called 'Reynolds number similarity'. Exceptions must be a) very small scale turbulence structure at dissipation, and b) flow fields very close to a boundary. Surfaces which are sufficiently rough exhibit Reynolds number similarity. Essentially all natural surfaces are aerodynamically rough; hence, flow structure will be similar if the scaled-down roughness has a sufficiently large size to prevent the formation of a laminar sublayer. Generally the requirement for fully rough flow is $U_* k \nu^{-1} > 100$ or $Re > 10^4$-10^6. The Rakaia Gorge model study considered above satisfied both these criteria. Replication of the main streamline features, regions of turbulent eddies, and structure of the turbulence thus becomes dependent upon geometric similarity and equivalence of relevant length scale ratios, such as $z_o L^{-1}$, $\Lambda_x L^{-1}$, *etc.*.

A large value of the <u>Richardson number</u> implies that buoyancy forces are very large compared to inertial forces. Thermal effects or density differences become less important as the Richardson number decreases toward unity. Stratification over complex terrain influences lee wave production, upstream waves, blocking, streamline separation and mixing processes. Batchelor (1953) has established that, if the flow fields are such that the pressure and density everywhere depart by only small fractional amounts from the values for an equivalent atmosphere in adiabatic equilibrium and if the vertical length scale of the velocity distribution is small compared to the scale height of the atmosphere, the Richardson number distribution governs dynamic similarity. But these conditions are only normally satisfied in the first 100 m of the planetary boundary layer. Flow fields with sufficiently large wind speeds and modest density gradients perceive only modest perturbations due to stratification. Unfortunately, elevated inversions may produce strong surface effects even when surface stratification is modest.

The Richardson number is not necessarily a difficult parameter to duplicate in a fluid model. Wind tunnel temperatures may be controlled by upstream heat exchangers, injection of heated air, or the use of a thermal boundary layer grown over long segments of heated or cooled surfaces (Plate and Cermak, 1963; Teunissen, 1975; Ogawa *et al.*, 1985; Schon and Mery, 1971). Water channels maintain stratification using either heat or, more frequently, layered salt water (Hunt *et al.*, 1978; Snyder, *et al.*, 1979). Unfortunately, to match model and prototype Richardson numbers for typical scale reductions of 1:500 to 1:5000 using reasonable model temperature or density differences, it is necessary to decrease the mean flow speeds substantially. Yet to match the Reynolds number requires large flow speeds; hence, a conflict arises.

The <u>Peclet number</u> is a measure of the ability of the fluid to advect heat or mass compared to its ability to disperse heat or mass by molecular transport. The Peclet number becomes important when Reynolds number independence does not exist. In such cases the relative ability of the fluid to transport heat or mass by molecular collision and the rate of transport provided by turbulent motions become comparable. Such a situation can produce incorrectly simulated plume entrainment and transport rates.

The Prandtl number and Schmidt number indicate the relative ability of the fluid to transport momentum versus its ability to transport heat or mass by molecular processes. If air is used to simulate the atmosphere, the Prandtl number is automatically satisfied, whereas the Schmidt number will be dependent on the model tracer gas chosen; however, both are usually close to a value of one. In water the Prandtl number is about 10 times larger than it is in air and varies with temperature. The Schmidt number for typical tracers such as sodium chloride or alcohol dispersing in water is nearly 800; hence, Schmidt number equality is unlikely in water facilities. Since both parameters always appears in the governing equations multiplied by Reynolds number, the heat or mass Peclet number is actually the critical governing parameter.

The Eckert Number is the ratio of kinetic to excess internal energy, and it is equivalent to the Mach number squared. It is usually small compared to unity for both atmospheric and laboratory model flows. The Eckert number magnitude's small value in the energy equation suggests that viscous dissipation or compression do not affect atmospheric temperature distributions significantly.

2.3. Performance envelopes for fluid modeling

The viability of a given simulation scenario is not only a function of the governing flow physics but also the availability of a suitable simulation facility and the measurement instrumentation to be employed. It would seem appropriate, therefore, to suggest bounds for the range of field situations which can be reasonably treated by physical modeling. This discussion is limited to wind tunnels and a separate evaluation can be made for water channels. Typical meteorological wind tunnel characteristics are listed in Table I. A comparison between field and laboratory parameter ratios is provided in Table II.

<u>Neutral airflow models</u>

When one combines various operational constraints into a performance envelope, a clear picture appears of the performance region for wind tunnel facilities. Figure 1 is such a performance envelope prepared for a large facility (3 m x 4 m x 25 m test section dimensions). The criteria selected to specify operational simulation ranges are:

Maximum model height ($h \le 0.5$ m),
Minimum convenient model height ($h \ge 0.02$ m),
Minimum Reynolds number ($Re = Uh\nu^{-1} \ge 10^4$),
Maximum model integral scale ($\Lambda_x \le 0.5$ m),
Minimum model integral scale ($\Lambda_x \ge 0.05$ m),
Minimum model measurement resolution ($\Delta z \ge 0.1$ mm),
Maximum model boundary depth ($\delta \le 2$ m), and
Minimum model boundary depth ($\delta \ge 0.1$ m).

Since field values for some parameters are uncertain the prototype value of δ and Λ_x are assumed to range over complex terrain as follows,

$300 \text{ m} < \delta < 1000 \text{ m}$, and

$100 \text{ m} < \Lambda_x < 1000 \text{ m}$.

Not all previous laboratory studies meet such similitude restrictions. Some experiments were performed to meet objectives other than similitude of turbulence or mean velocity profiles; nevertheless, a number of such studies are indicated on Figure 1. In almost all cases noted values fall within or just outside the proposed operational envelope.

Based on Coriolis force considerations, Snyder (1972) suggests 5 km should be the maximum distance for horizontal length scales when modeling diffusion under neutral or stable conditions over relatively flat terrain. Mery (1969) suggests a 15 km limit, Ukejurchi *et al.* (1967) suggest 40 to 50 km, and Cermak *et al.* (1966) and Hidy (1967) recommend 150 km. A middle road value would be that of Orgill *et al.* (1971) who suggest for rugged terrain in high winds that a length scale of 50 km is not unreasonable.

Assuming an upper limit for length scale ratio of 10,000 and a tunnel length of 25 m, then a 50 km fetch in the windward direction is well within the capacity of many existing facilities. Assuming a lateral width restriction of 4m suggests a 40 km lateral maximum for the field area modeled.

<u>Stratified airflow models</u>

One must add the additional constraints of stratification to the envelope produced in Figure 1. In this case reduced model wind speeds imply an interactive relationship between the surface roughness, surface layer Richardson number, and hill Froude number parameters. Assuming that roughness height to hill height ratio will be $kh^{-1} \leq 0.1$, then the aerodynamic roughness Reynolds number will be $Uk\nu^{-1} \geq 4000$. Furthermore, assuming that the thermal gradients in the atmospheric surface layer extrapolate to the terms required in the Froude number through power law relationships, the length scale ratio, LSR, must be

$$\mathrm{LSR} \leq \left[\left(\frac{h^2}{4000\ \alpha\nu}\right)\left(\frac{10}{h}\right)^{1-\alpha}\left(\frac{(\partial T/\partial z)_m g}{T\ Ri_{10}}\right)^{1/2}\right]^{1/2} \tag{1}$$