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PHYSICAL SIMULATION OF DISPERSION IN COMPLEX TERRAIN AND VALLEY DRAINAGE FLOW SITUATIONS

Robert N. Meroney§

Institut Wasserbau III
Sonderforschungsbereich 80
University of Karlsruhe
7500 Karlsruhe 1, B.R.D.

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.

Successful modeling of some of the more complex atmospheric surface layer phenomena in a wind tunnel has only been accomplished in the last fifteen years. Although guidelines for modeling flow over complex terrain are essentially similar to those for modeling that around

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§ Von Humboldt Foundation Senior Scientist from
Fluid Mechanics and Wind Engineering Program
Colorado State University
Fort Collins, Colorado 80521, USA

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buildings a few unique features will be discussed herein. The characteristics of wind and diffusion over complex terrain which limit physical modeling and stipulate simulation criteria are reviewed only briefly. For a more extensive background the reader is referred to reviews on diffusion in complex terrain prepared by Eagan (1975), discussions of flow over terrain by Meroney et. al. (1978), or recent symposium proceedings devoted exclusively to the subject Johnson (1979).

WIND CHARACTERISTICS IN COMPLEX TERRAIN

Mountains may alter atmospheric airflow characteristics in a number of different ways. These effects can generally be grouped into those due to inertial-viscous interactions associated with a thick neutrally stratified shear layer and to thermally induced interactions associated with stratification or surface heating.

Neutral Airflow Over Hilly Terrain

Near-neutral or adiabatic atmospheric boundary layers will exist over mountains during situations when winds are high due to intense synoptic pressure fields, when continous cloud banks impede surface heating, and when sharp terrain features produce separation eddies which mix the flow field vigorously in the vertical.

When the static stability is neutral, airflow over mountains creates pressure gradients in the flow direction, which together with surface friction, may produce separation, flow reversal, and reattachment. Separation eddies at the windward or leeward side of a mountain can alter the effective shape of the mountain resulting in a modified wind profile at the crest. Scorer (1978) describes eight different variations of the separation phenomenon. He notes that separation may be changed in character by insolation, blocking, diabatic changes, and three-dimensional effects.

Meroney et al. (1978) summarized experimental data available from field and laboratory structures over hills, ridges, and escarpments. Orgill (1977) surveyed wind measurements programs that have used wind networks (2 to 60 measurements sites) to identify details at atmospheric surface layer behavior. Out of the 139 field programs 3 relate to an isolated mountain, 7 to mountain-plain flows, and 20 to complex topography.

Arya and Shipman (1978) review past measurements of diffusion near shelter belts and simple barriers. They report that when an elevated source is located upwind of an isolated ridge or at the ridge top, the effect of ridge is generally to reduce the ground-level concentrations. For low-level sources, however, the maximum ground level concentration (g l c) in the cavity region may become much larger than the maximum g l c without the ridge, if a large part of the plume impinges on the separation streamline and becomes trapped in the cavity region. Thus the ground-level concentrations downwind of the ridge are very sensitive to source height and position. When the source is located in the lee of the ridge, increased turbulence in the wake results in much lower concentrations aloft, but higher concentrations at the ground level. Maximum g l c occurs when the source is located within the cavity region near the base of the ridge. The peak concentration decreases and its position shifts farther downwind from the source as the source height and distance from the ridge increase. The ridge also influences considerably the vertical concentration profiles. Recent field measurements of dispersion in complex terrain may be typified by those of Start et al. (1975) who report the following differences for Huntington Canyon and flat terrain diffusion: "Neutral stability tests showed five times greater dilution for canyon axial concentrations; strong inversion tests resulted in canyon plume centerline dilutions fifteen times greater than calculations using parameters derived for flat terrain". It was concluded that plume dilutions in Huntington Canyon were affected by such physical mechanisms as enhanced mechanical turbulence associated with gradient windflows near the mountain tops, density flows originating in side canyons, and turbulent wakes from pronounced terrain irregularities.

Stratified Airflow Over Hilly Terrain

Stratification has a strong effect upon flow over and around hills. The intensity of an inversion may influence both wind velocity and direction. If inversions are frequent, acceleration of air around the hillside rather than over the hilltop may lead to larger annual average velocities away from the hill crest. Stratified flow over mountain ridges may also lead to lee waves or helm winds. There is very extensive literature dealing with orographic induced waves, but since most of it deals with cloud systems and upper atmosphere character far from the surface, it is not very helpful for dispersion analysis. Slope and valley airflows when dominated by surface heating or cooling often result in quite complicated secondary flows. According to Munn (1966) the important properties of valley airflows are:

1. Orientation of the geostrophic wind,
2. Orientation of the valley (a north-south valley has a different

radiation balance from one lying in an east-west direction), and

3. The geometric dimension of the valley, such as length, width, depth, side slopes, slope of the floor and the number of bends or constrictions.

When a strong geostrophic wind blows parallel to a valley a funneling effect occurs. If the valley narrows, the wind is speeded up as it passes through the valley. If the geostrophic wind is blowing at right angles to the valley a large cross valley circulation or "valley eddy" may be formed. The wind is a combination of up and downslope winds and the background synoptic flow modified by the mountains. During high wind speed conditions ($U_{10} > 5$ m/sec) slope heating plays a minor role and the valley behaves as another perturbation on a natural adiabatic shear flow approximation.

Dispersion data and detailed wind information for valley drainage flows is lacking. Draxler's (1979) survey of recent atmospheric dispersion experiments includes 5 data sets for rough terrain, and only 1 for valley drainage situations.

CRITERIA FOR LABORATORY SIMULATION OF FLOW CHARACTERISTICS OVER IRREGULAR TERRAIN

In order for the flow in any laboratory model to be of value in interpreting or predicting the observed flow in the atmosphere, it is essential that the two flow systems should be dynamically, thermally and kinematically similar. This means that the flow in the two systems must be described by the same equations after appropriate adjustments of the units of length, time and other variables.

A number of authors have derived the governing parameters for atmospheric heat, mass, or momentum transport by dimensional analysis, similarity theory, 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. Although all investigators do not agree concerning details, most would concur that the dominant mechanisms can now be identified and are understandable. The following sections review similitude criteria as they relate to adiabatic and stratified flows over irregular terrain. Restrictive assumptions are discussed and a typical performance envelope for a large wind tunnel facility is provided.

Neutral Airflow Models

The pertinant parameters for steady turbulent, near neutral airflows are undistorted scaling of topographical features; Reynolds number ($U \; L / \nu$) independence; Rossby number ($U / L \Omega$) independence; and kinematic similarity of approach flow, i.e., distributions of mean velocity and turbulence.

Over irregular terrain the flow characteristics are only weakly dependent on Reynolds number when the surfaces are aerodynamically rough, i.e., the flow structure will be similar if the scaled roughness has a sufficient size to prevent the formation of a laminar sublayer. Generally the requirement for fully rough flow is satisfied if one stipulates model conditions such that

$$\frac{U h}{\nu} > 10000$$

where h is average hill or mountain height, and either

$$\frac{k \; u_*}{\nu} > 20 \qquad \text{or} \qquad \frac{k \; U}{\nu} > 400$$

where k is roughness height and u_* is friction velocity (Snyder, 1979). When terraced models are constructed the individual terrace height should be O(k). In addition an upstream model fetch should include any ridge whose height exceeds one-hundredth of the fetch distance, i.e., $h > x/100$, or any hill or mountain whose height exceeds one-twentieth of the fetch distance, i.e., $h > x/20$. The fetch indicated is of course upwind of any proposed gas release, and an additional fetch required for equilibrium boundary layer development must be added.

Over irregular terrain the flow field may be assumed Rossby number independent for distances from 10 to 50 km. Hoxit (1973) and Scorer (1978) observe that most of the time atmospheric flows are not in equilibrium with Coriolis forces because of thermal winds; hence the simulation of the Ekman spiral is normally only of academic interest. For flow over flat terrain an upper limit to model length due to shear effects on dispersion may be 5 to 10 km.

Stratified Airflow Models

The pertinant additional parameters for steady stratified airflows are bulk Richardson number ($g \Delta\theta \, \delta / \theta \Delta U^2$) equality over the surface layer, Froude number ($\Delta U^2 \; \theta / g \Delta\theta \; h$) equality over the mountain or hill height, and sufficient lateral and longitudinal model extent to account for effects of surface flow blockage or channeling. In the case of the model airflow the potential temperature, θ, may be replaced by temperature or density.

Equal gross or local Richardson numbers can be obtained in specially designed wind tunnels. 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 scale of the velocity distribution is small compared to the scale height of the atmosphere, the Richardson number distribution governs dynamical similarity. Unfortunately, these conditions are only normally satisfied in the first 100 m of the planetary layer. Batchelor has emphasized that no single local, variable quantity can be used as a similarity parameter. Similarity parameters can have meaning only when they characterize the gross features of the flow.

Snyder (1979) found that for plumes transported toward three dimensional hills in stratified flows simulation of the stability above the thin surface layer is most important to reproduce the essential features of the flow, i.e., whether plumes will impinge on the hill surface or travel over the hill top. Unfortunately in the process of meeting the Froude number criteria based on mountain height it is possible the wind tunnel duct Froude number may fall too low, i.e., $Fr_D < 1/\pi$. In this case undesirable standing wave systems tend to appear just downstream of the tunnel heat exchanger at the entrance (Yamada and Meroney, 1974).

Valley Drainage Airflow Models

Local heating and cooling of hill surfaces are the driving mechanisms for anabatic and katabatic winds which inhibit or enhance separation over hill crests. Laboratory models to simulate such conditions must still be considered largely exploratory in nature at this time. Early work includes simulations of urban heat islands by Yamada and Meroney (1971) and Sethuraman and Cermak (1974), simulation of flow and dispersion at shoreline sites by Meroney et. al. (1975), and simulation of dispersion effects of heat rejected from large industrial complexes by Meroney et. al. (1975).

Equality of a Monin-Obukhov type length scale ratio is appropriate for surface heating situations with a finite cross flow wind field, i.e. L/L_{mo}, where L_{mo} is the Monin-Obukhov stability length. In terms of a bulk parameter this would be

$$\frac{U_m^3 \theta_m A_m L_p Q_p}{U_p^3 \theta_p A_p L_m Q_m} = 1.0$$

where Q is the total heat flux to the atmosphere, L is a vertical reference scale, A is the surface area heated or cooled, θ is the average ambient temperature, and U is the ambient reference air speed (m and p refer to model and prototype conditions). Unfortunately momentum and heat flux information are often not conveniently available for the field or model. In addition calculations indicate that the modeled heat flux is very sensitive to velocity changes with background stability.

Similarity between the flow generating mechanisms of sea breezes and flow over certain heat islands suggests alternative parameters. Linear numerical analysis of Olfe and Lee (1971) and experimental and numerical studies by Yamada and Meroney (1971) suggest the intensity of heating or cooling by the land surface may be characterized by a heating ratio

$$HR = \frac{\Delta \theta_z L_x}{\Delta \theta_x L_z}$$

where θ_z are characteristic changes in temperature over a vertical scale L_z and θ_x are similar changes over some horizontal scale L_x. Since the vertical-to-horizontal modeling scale is undistorted, the parameter reduces to a single temperature ratio.

In those situations where the gradient wind is extremely small and where the lateral variations in surface temperature are negligible, another parameter called the Rayleigh number $(g\beta(\theta_w-\theta_H)\, h^3/\nu\alpha)$ is appropriate. One notes that the scaled temperature potential increases as the model scale cubed!

As one can imagine there can be no firm and fixed rules for determing the appropriate terrain area or simulation constants to model until the flow situation is well defined. Nonetheless a fluid model study does employ a "real" fluid; hence a well designed and carefully executed fluid model study will yield valid and useful information.

PERFORMANCE ENVELOPE FOR WIND TUNNEL MODELING OF AIR-FLOW OVER COMPLEX TERRAIN:

The viability of a given simulation scenario is not only a function of the governing flow physics but 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 fiels situations which can reasonably be treated by physical modeling.

A number of boundary layer wind tunnels exist at various laboratories. Generally these tunnels range in size from facilities with cross-sections of 0.5 m x 0.5 m to 3 m x 4 m. Several of these facilities are equipped with movable side walls or ceilings to adjust for model blockage. By utilizing a variety of devices such as vortex generators, fences, roughness, grids, screens, or jets a fairly wide range of turbulence integral scales can be introduced into the shear layer. Varying surface roughness permits control of surface turbulence intensity, dimensionless wall shear, and velocity profile shape. Density stratification can be induced by means of heat exchangers, use of different molecular weight gases, or latent heat absorption or release during phase changes. A comparison between field and laboratory parameter ratios are summarized in Table 1.

Neutral Airflow Models

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

Maximum model height ($h \leq 0.5$ m)

Minimum convenient model height ($h = 0.02$ m)

Minimum Reynolds number ($Re_h = U h/\nu = 10{,}000$)

Maximum model integral scale ($L_{u_x} \leq 0.5$ m)

Minimum model integral scale ($L_{u_x} \geq 0.05$ m)

Minimum model measurement resolution ($\Delta_z \geq 0.1$ mm)

Maximum model boundary depth ($\delta \leq 2$ m)

Minimum model boundary depth ($\delta \geq 0.1$ m)

Since field values for some parameters are uncertain the prototype value of δ and L_{u_x} are assumed to range over complex terrain as follows

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

$100 \text{ m} < L_{u_x} < 1000$ 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

Table 1: Typical Wind Tunnel and Field Parameter Range

DIMENSIONLESS PARAMETER	WIND TUNNEL RANGE	FIELD RANGE
Reynolds number $Re_h = U h/\nu$	$0 \rightarrow 7.0 \times 10^5$	$0 \rightarrow 6.0 \times 10^6$
Richardson number $Ri_B = \frac{g}{\theta} \frac{(d\theta/dz)\,h}{U^2}$	$-1.0 \rightarrow 1.0$	$-1.0 \rightarrow 1.0$
Prandtl number $Pr = \mu c_p/k$	0.72	0.72
Skin friction coefficient or Stanton number $\frac{C_f}{2} = \frac{\tau_w}{\rho U^2} = \left(\frac{u_*}{U}\right)^2$, $St = \frac{q}{\rho c_p(\Delta T)}$	$0.005 \rightarrow 0.004$	$0.001 \rightarrow 0.004$
Scaling lengths		
z_o/h	$2 \times 10^{-5} \rightarrow 0.25$	$3.0 \times 10^{-7} \rightarrow 0.15$
δ/h	$0.20 \rightarrow 50.0$	$0.10 \rightarrow 100$
$(L_{u_x})/L$	$0.06 \rightarrow \infty$	$0.001 \rightarrow \infty$
h/L_{MO}	$0 \rightarrow 5.0$	$-360 \rightarrow 240$
Power law coefficient α	$0.05 \rightarrow 0.8$	$0.05 \rightarrow 0.7$

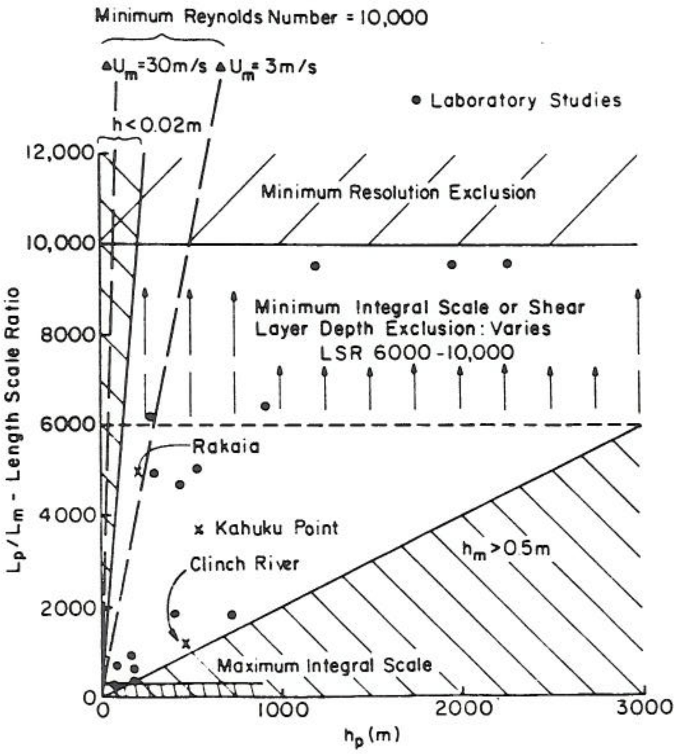

Figure 1: Performance Envelope for Physical Modeling of Shear Flows over Complex Terrain

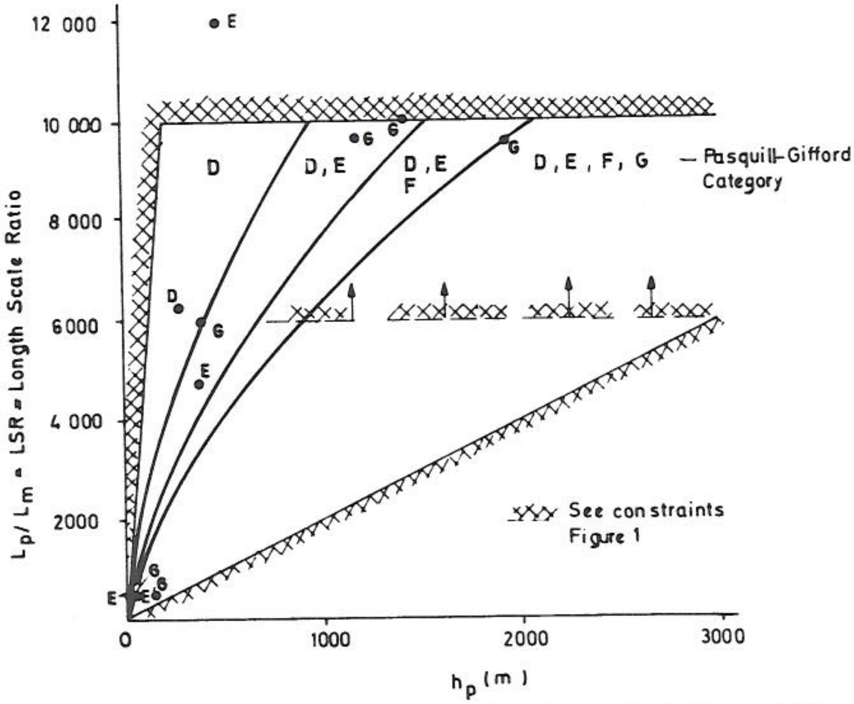

Figure 2: Performance Envelope for Physical Modeling of Steady Stratified Shear Flows over Complex Terrain

studies are indicated on Figure 1. In almost all cases noted values fall within the indicated operational envelope or just outside the predicted region.

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

Stratified Airflow Models

One must add the additional constraints of stratification to the envelope produced in Figure 1. In this case reduced model wind speeds imply a interactive relationship between the surface roughness, surface layer Richardson number, and hill Froude number parameters. If one assumes that roughness height to hill height ratio $k/h \leq 1/10$, then the aerodynamic roughness ratio is $hU/\nu \geq 4000$. If one further assumes that the thermal gradients on the surface layer extrapolate to the terms required in the Froude number through power law relationships then the length scale ratio, LSR, must be

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

where

$(\partial T/\partial z)_m$ = maximum thermal gradients in model (1 °C/cm)

h = prototype characteristic hill height

Ri_{10} = characteristic Richardson number at a reference height of 10 meters

α = $\alpha(Ri, z_o)$ = velocity power law exponent = (0.1 to 0.5)

Here Ri_{10} and α may be stipulated emperically for the various Pasquill-Gifford stratification categories. Figure 2 displays the result of stratification limitations on a performance envelope.

Valley Drainage Flows

Stipulation of strict Rayleigh number similarity would essentially eliminate the possibility of modeling valley drainage flows; however gravity current movement down steep valley walls will result in high local Reynolds numbers and turbulent mixing. In such circumstances the appropriate viscous parameter is the eddy viscosity, $\epsilon = UL$, not ν. Substitution of this variable transforms the Rayleigh number into the Richardson number introduced earlier. Aluminum shell models (LSR = 1920 and 2560) cooled by dry ice have been used by Petersen and Cermak (1980) to study drainage flows in the mountains near Crested Butte, Colorado. Richardson numbers based on the maximum surface jet velocity and jet height were found to vary from 0.5 to 2.0. These produced surface velocities equivalent to 1.0 to 3.5 m/s between 50 to 150 m above the ground. Specific field conditions were not chosen in advance; rather model conditions were permitted to develop, and the equivalent field conditions were evaluated from the measured Richardson numbers.

VERIFICATION EVIDENCE

Not all of the cases identified on Figures 1 and 2 were successful. Many early studies had model approach flow velocity exponents near zero, were modeled as neutral flows when the field observed strong stratification effects, or simulated unrealistic boundary layer depths, integral scales, or turbulence intensities which did not match their atmospheric counterpart. Several of the investigations on Figure 2 seem only marginally realistic. Since plumes tend to travel undiluted for long distances in stable flow there is a tendency for the investigator to select as large a scale ratio as possible. Since a plume's lateral displacement over irregular terrain is determined primarily by gorge or valley meandering in stable flow even these studies may be similar to field experience.

In seventeen of some forty physical model studies examined by the author, which were performed over idealized or specific irregular terrain, there are some counterpart field data available (Meroney et. al., 1978). Few studies claim unreasonable correlation, and some are strongly self-critical. Nonetheless most studies accomplished their prestated limited objectives. Several recent cases are examined briefly in this paper to represent the degree of similarity possible.

Time and Space Scales Appropriate for Physical Modeling

The joint consideration of time and space scales modeled in atmospheric boundary-layer wind tunnels may be overlaid upon the characteristic time and horizontal scales of atmospheric phenomena. Such an overlay upon the atmospheric scales defined by Orlanski (1975) has been proposed in Meroney et. al. (1978). The wind tunnel may study phenomena up to the mesoscale in time and into the mesoscale in length with reasonable credibility.

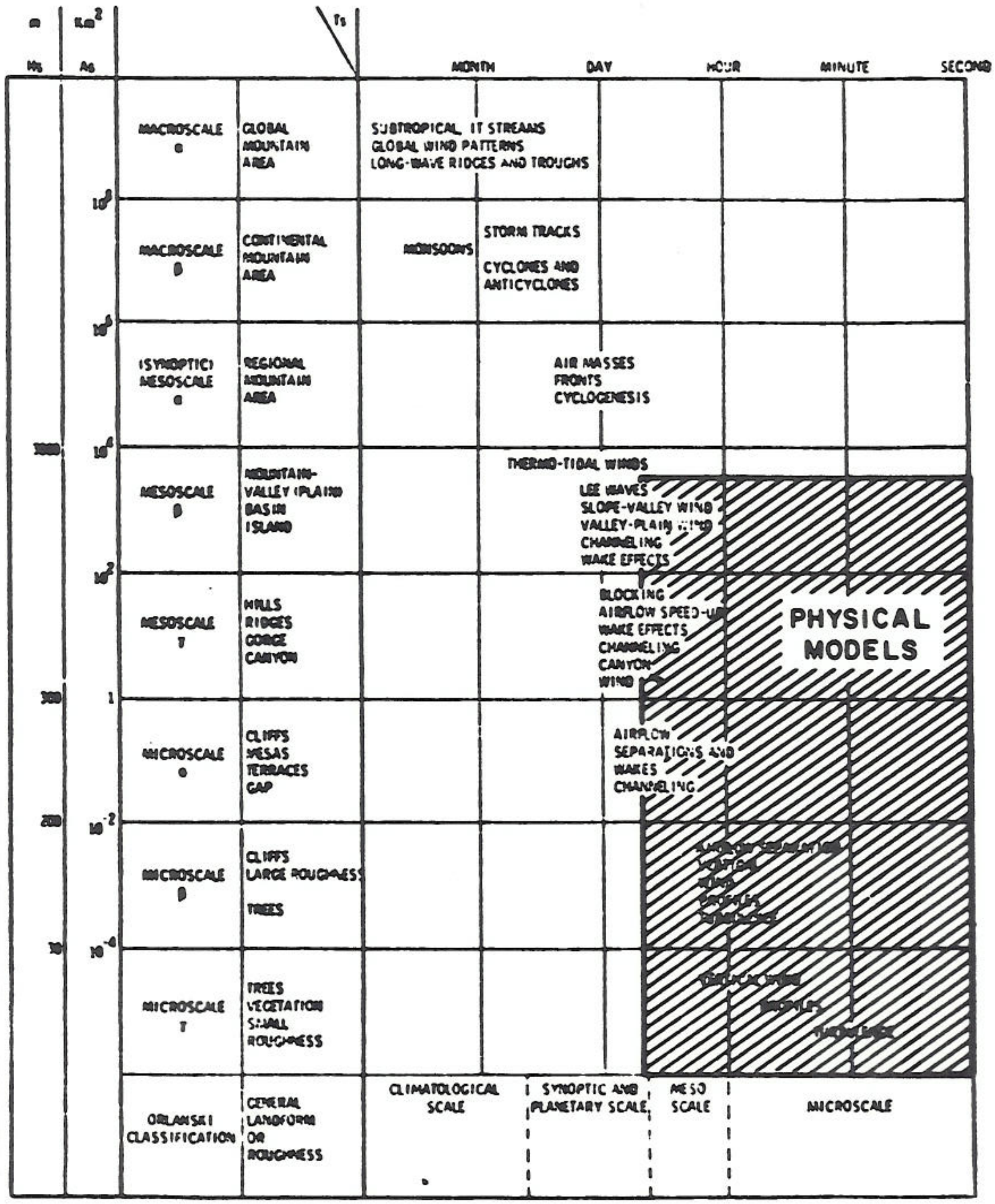

Figure 3: A Classification of the Effects of Terrain on Atmospheric Motions. After Orlanski (1975)

When the performance evelope of physical modeling by wind tunnels is superimposed upon the scale effects produced by terrain on atmospheric motions Figure 3 is obtained. Only the time scales associated with turbulence or advection over terrain are realistically included in current physical modeling repertoire. The fluctuations in a field of motion associated with diurnal variations in the atmosphere or with weather fronts are not developed in physical models considered to date.

One can, however, synthesize the average statistics of a flow field over longer time periods by associating a given measurement set with a recurring meteorological situation for which climatological probability distribution information is available. Hence it is possible to expand the physical model domain to longer time scales.

The inherent uncertainties associated with any atmospheric phenomena set bounds on any physical or numerical model verification exercise. One might say that the laboratory results simulate the average of many realizations of atmospheric flows whose boundary and initial conditions are "near" those of the laboratory model. Any single realization of atmospheric flow or diffusion over irregular terrain thus has a finite probability of varying from the mean behavior.

The prediction and model validation for scalar transport includes other uncertainties than those associated with errors in mean velocity, direction or turbulence. These include photomechanical effects, sinks, sources, depostion, etc. which are not generally modeled. Indeed scatter diagrams of numerical model to field results such as are provided by Duerver et. al. (1978) suggest correlations much less than 0.5 frequently occur; hence the cases reviewed herein will primarily examine flow field variables rather than diffusion.

Correlation of Laboratory and Field Experiments

The field/model studies discussed are three familiar to the author. One is the Rakaia River Gorge region on the eastern slope of the Southern Alps in New Zealand (Meroney et. al., 1980), the second is the Kahuku Point mountain-coastal region of Oahu, Hawaii, USA, (Chien et al., 1980), and finally the Clinch River valley in east-central Tennessee, USA, (Graham et al., 1979).

The Rakaia Gorge field study documented ten-minute wind speed and direction information at 27 sites during stationary conditions on two spring days selected for strong adiabatic down-valley wind flow. The Kahuku Point field study documented 24 hours average wind speed, turbulence, and directions at 32 sites during strong fall trade wind conditions. The Clinch River field study utilized a meteorological research aircraft and a 110 m meteorological tower to monitor velocity, turbulence, temperature, humidity, and direction. The aircraft flights were made during unfortunately light wind conditions and averaged over 15 second periods; nonetheless the tower data were available for strong wind situations comparable to those simulated over the model.

In the Rakaia Gorge and the Kahuku Point cases measurements were compared point to point, scatter diagrams constructed, and sample correlation coefficients calculated. If simulation is good there must be a high linear casual relationship between measurements in the field and laboratory. The best estimation of the population correlation is the sample correlation coefficients which have been added to Table 2. Apparently wind velocities and directions may be expected to correlate with field data at a level of $r \geq 0.7$. Recently Holmes et al. (1979) also reported a comparison field and laboratory measurements of maximum gust velocities over Castle Hill (286 m) near Townsville, Australia. Linear correlation coefficients ranging from 0.68 to 0.78 were obtained.

Specific features of flow over irregular terrain were looked for in both field and model data as noted in Table 3. Similar behavior was observed in each case within the limitations of the descisions to model or not model stratification effects.

Recent valley drainage model experiments still await counterpart field data (Petersen and Cermak, 1980). It is hoped that the current DOE-ASCOT (Dept. of Energy - Atmospheric Studies in Complex Terrain) studies over the Geyser area in California will fill this gap. Nonetheless qualitative features of valley drainage flows observed by meteorologists elsewhere were observed over the model. These include secondary cross currents caused by valley wall drainage, down valley jets, etc.

CONCLUSIONS

The objective this paper addressed was to identify pertinent similarity criteria for physical modeling of flow over complex terrain. Verification required a comparison between specific laboratory full scale experiments. A review of previous physical modeling experience provided an index of some forty case studies relevant to terrain modeling techniques. Seventeen investigations included some field comparables. The three studies discussed were designed to specifically test various model alternatives. Criteria for laboratory simulation of wind characteristics over

Table 2: Field to Model Data Correlations

Model or Flow Characteristic	Rakaia Gorge New Zealand Field*	Model	Kahuku Point Hawaii Field*	Model
Area of Interest (km^2)	112	112	155	155
Hill Height (m)	240	240	500	500
Model Scale	-	5000	-	3840
Power law - α	0.14±.02	0.13-0.14	0.14±.02	0.13-0.15
Roughness - z_o (m)	0.05	0.045	0.11	0.11
Turbulence - u'/u_{10}	0.14±.05	0.14-0.15	0.15±.03	0.12-0.18
Shear - $\sqrt{u'w'}/u_{10}$	0.0020	0.0019	0.0064	0.0074
Boundary depth (m) δ	750±250	500	600±300	600
Integral Scale L_{u_x} (m)	900-1000	600	167	100-120
△ Correlation Velocities	0.68-0.78		0.71	
△ Rank Correlation Velocities	0.78-0.95		0.84	
△ Correlation Wind Directions	0.65-0.67		-	

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* Counihan (1975)

△ Compared point by point to field program

Table 3: Features of Flow Over Irregular Terrain

Model or Flow Characteristic	Rakaia Gorge New Zealand		Kahuka Point Hawaii		Clinch River Tennessee	
	Model	Field	Model	Field	Model	Field
Approach Flow Characteristics (i.e. α, z_o, u'/u, etc.)	S	S	S	S	S	S
Velocity over ridge crests	O	O	O	O	O	O
Decreased turbulence intensity over ridge crests	O	O	O	O	O	O
Increased turbulence intensity downwind of hills	O	O	O	O	O	O
Wind veering in gorges	O	O	-	-	-	-
Wind veering around hill sides	O	O	O	O	-	-
Increased turbulence downwind of coastal beach	-	-	O	O	-	-
Irregular wind and turbulence in sheltered areas	O	O	O	O	-	-
Wind veering during sea breeze and valley drainage situations	NM	-	NO NM	O	NM	-
Increased Dispersion downward of ridges	NM	-	NM	-	O	O

S - simulated
O - observed during field program
NM - not modeled
NO - not observed

irregular terrain in general have been summarized.

It would appear that the simulation wisdom developed in the past few years is appropriate for physical modeling of flow over complex terrain. Since the flow region of interest is usually in the lower surface layer ($z < 250$ m), great care must be taken that horizontal nonhomogenuities in roughness and terrain are faithfully reproduced. Specific conclusions from the cited studies suggest that:

1. Un undistorted model at scales as large as 1:5000 permits resolution of velocity and turbulence details adequate to reproduce scalar dispersion.

2. A wide range of scales and meteorological conditions may be simulated in existing boundary layer wind tunnel facilieties; (see Performance Envelopes Figures 1 and 2).

3. To produce equivalent wind speeds near ground level requires accurate reproduction of surface roughness, shape, and vegetation effects. Terraced models, adequate for certain dispersion simulations where the plume is aloft or of large size compared to terrace depths, are inappropriate when the plume is at ground level and of a scale comparable to those of terrace depth.

4. Current meteorological data in complex terrain is not yet adequate to stipulate inflow conditions to physical models with confidence. Hence an adequate approach flow length must be provided to allow the surface layer to come to an equilibrium with underlying terrain undulations.

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