Gebbies Pass, Banks Peninsula, New Zealand

In a similar research program Neal *et al.* (1980) prepared a set of 1:4000 scale models of the pass (or saddle) which crosses the lip of an ancient volcano today known as Banks Peninsula, New Zealand. Measurements of wind speed and turbulence were compared with field measurements. The sample correlation coefficients ranged from 0.88 to 0.90, and the rank correlation of wind stations by wind speed was 0.98.

Kahuku Point, Oahu Island, Hawaii

Chien *et al.* (1980) measured flow perturbations over an undistorted 1:3840 scale model of the Kahuku Point peninsula in a meteorological wind tunnel. Daniels and Oshiro (1980) measured continuous hourly averaged data over the site for a two month period during the fall of 1978 using mobile measurement stations and tethered balloons. Relative wind speeds for each measurement site were compared based on a normalization by an equivalent fixed reference site. Based on field measured wind directions an equivalent relative speed of each site was obtained from the laboratory data using a weighted average approach. The sample correlation coefficient obtained between the field and laboratory data was 0.71, and the relative wind speed rank test correlation was 0.84. Wind speedup over the hilly terrain was also predicted using the methods of Bouwmeester *et al.* (1978) and Hunt (1978) which were based on experience with two-dimensional idealized hills. Bouwmeester's technique tended to overpredict crest speedup by about +16%, whereas the Hunt method underpredicted winds by -18%. Thus, the two methods bracketed typical topography amplification.

Askervein Hill Project, Outer Hebrides, Scotland

The Askervein Hill project was a collaborative study of boundary-layer flow over low hills (Taylor and Teunissen, 1985). Two field experiment were conducted during fall 1982 and 1983 near and around Askervein, a 116 m high hill on the west coast of the island of South Uist in the Outer Hebrides of Scotland. Over 50 towers were deployed and instrumented for wind measurements. Most were cup anemometers mounted on simple 10m posts, but two 50m, a 30m, a 16m, and thirteen 10m towers were instrumented for 3-component turbulence measurements. Subsequently, wind tunnel simulations of neutrally-stable atmospheric boundary-layer flow over the hill were carried out at three different length scales (1:800, 1:1200, and 1:2500) and in two wind-tunnel facilities (Teunissen *et al.*, 1987). The objective of the laboratory measurements was to determine the relative impact of varying surface roughness, model scale and measurement techniques. The wind-tunnel results compared well with each other and with full-scale data, Figure 22 and Figure 23. The main conclusions of this work were:

a. Changes in mean flow speed-up over a physical model are reproduced very well, including those due to small, local terrain features which may be physically extremely small at model scale,

b. Relaxation of the aerodynamic roughness criterion affected the flow only on the lee side of the hill. Turbulence changes induced by the hill did not depend on the nature of the surface roughness. An excessively smooth surface reduced the degree and extent of separated flow and resulted in overestimation of hill crest wind speeds,

c. Simulations in two facilities using three models at three different scales showed a gratifying degree of consistency. The only effect of model scale was a predictable increase in difficulty in making measurements very close to the surface as size of the model decreased, and

d. Depth of the turbulent inner layer was less than that suggested by Jackson and Hunt's (1975) relationship, but similar to the value predicted by Jensen *et al.* (1984).

### 4.4. Conclusions from neutral airflow terrain studies

Physical modeling experience from studies performed over idealized two- and three-dimensional hills and scale models of complex actual complex terrain reveals:

@ The gradient of velocity with height at ridge crests is usually small,

@ Except for very small slopes (< 1:10) the amplification factor, A, or fractional speed up, $\Delta S$, varies with height,

@ Hills of different shape, but equivalent average slope give similar profiles when separation is absent,

@ Separation at hill crest is a function of both upwind and downwind slopes,

@ Three dimensional hills do not produce speed up as large as similar section ridges,

@ For small and moderate length hills turbulence intensity decreases at hill crest since only pre-existing turbulent energy is convected over the hill,

@ Potential or inviscid-rotational numerical calculations predict unseparated flows very well,

@ Undistorted models at scales as large as 1:5000 permit accurate resolution of velocity and turbulence details,

@ Replication of near-ground wind speeds and separation requires careful attention to local surface features and the presence of vegetation,

@ Relaxation of the criteria of Roughness Reynolds number to values near $Re_* = Uz_o\nu^{-1} = 0.4$ is permissible, and

@ Careful measurements over different models in different facilities produce equivalent results.

## 5. Stratified flow over hills and ramps

There is extensive literature which deals with stratified channel flow and tank experiments performed to examine the perturbations generated by obstacles in stratified fluids (Turner, 1973; Gebhardt, 1988; Simpson, 1987, *etc.*). Similar experiments have been performed in wind tunnels (Lin and Binder, 1967), but normally it is easier to produce stratification and attractive visualization in water. The purpose of such experiments is to gain understanding about the role stratification, upper boundaries and terrain form play in air flow patterns, wave generation, blockage, and turbulent mixing.

5.1. Idealized two-dimensional flow domains for waves and blocking

Flows induced by combinations of stratification and surface obstructions can be extremely complex and intriguing. But even flows of a single laboratory liquid layer over a two-dimensional model ridge can induce surface motions very similar to the inversion layer movements observed in the atmosphere. Figure 24 displays the five domains of flow behavior observed for different combinations of Froude number, $U^2(gh)^{-1}$, and hill height ratio, $hD^{-1}$. When the ridge to inversion height ratio is small and wind speeds are large winds will flow over a ridge in a symmetric rapid-flow pattern (Figure 24a), but as the relative ridge height increases or wind speeds decrease then mountain waves (Figure 24b), Föhn walls (c), hydraulic jumps and rotors (d), and even upwind blockage (3) may occur. Gradients in vertical stratification and the presence of additional elevated inversions will change both the quantitative and qualitative appearance of the winds.

Baines (1979) performed finite-water-depth tow tank experiments over small obstacles ($hD^{-1} = 0.076$) for a wide range of stratification conditions ($K = ND(\pi U)^{-1} = 0.5$ to 3.0). He determined that no upstream waves occurred for $K < 1$, but complex waves, columnar upstream disturbances, overturning, and blockage occurred when $K > 1$. There was some concern expressed as to whether the results were distorted by the presence of a reflective water surface lid during the experiments. Baines and Hoinka (1985) presented additional tow tank experiments in a water channel designed to remove surface reflections and simulate an infinite depth stratified fluid, Figure 25. They determined that upstream disturbances could be induced in stratified flows even in the absence of an upper boundary. Criteria for the presence of columnar upstream motion and blocking in terms of K for various obstacle shapes were proposed as show in Figure 26.

5.2. Downslope winds, valley fLows induced by cross-winds

Tampieri and Hunt (1984) used a small water channel to examine the behavior of stratified flow over two successive humps. The two ridges were of small to moderate slope (between 0.25 to 0.5); the distance between them varied between being slightly less than to much greater than the wavelength, $\lambda$, of internal gravity waves or lee waves, Figure 27. Over a narrow range of Froude number, $F_L$ (based on hump half length L) such that the natural lee wavelength is about equal to the valley width D, and for a particular ratio D/L near six, the valley is ventilated without significant regions of separation. At other values, there was some recirculation and stagnation of the flow, Figure 28. They suggested that it is not sufficient for the length of the natural lee waves to equal the spacing between the humps to produce ventilation, but it is also necessary for the higher speed flow on the lee of the first hump to overcome the slowing down of the flow by the downwind hump. Finally, surface winds are expected to be greatest on the lee slope of the second hump.

### 5.3. Idealized three-dimensional terrain studies

Stratified three-dimensional laboratory studies have been directed to find a) whether streamlines from upwind impinge, go round or go over a hill, b) the size and location of internal jumps, waves and separated or recirculating flow, c) the effects of heating of cooling the surface, and d) differences between two and three-dimensional flow fields.

The work of Hunt and Snyder (1980) focused on the concept of a separating stream line which divided regions where flow went around a hill versus over the crest, Figure 29. Colored dye visualization of stratified flow about a polynomial shaped hill revealed that for $F \ll 1$ the flow is approximately horizontal except in narrow regions at the top and bottom of a hill. For $F > 1.5$ flow over the hill was essentially neutral. When $F < 0.8$ separation is suppressed at the top of the symmetric hill. The criterion for determining whether the plume will impact on the hill surface and go round the sides or go over the top was found to be, roughly, $H_s = h(1 - F)$, where $H_s$ is the dividing streamline height, h is the hill height, and F is the Froude number characterizing the stratification, Figure 30. Later Snyder *et al.* (1985) compared stratified flow two tank results for flow over a 1:690 scale model of Cinder Cone Butte, Idaho, with field data and the separated streamline theory. Laboratory experiments also alerted investigators to the extreme sensitivity of surface concentration patterns around hills to wind direction--a 5 degree in wind direction shifted surface plumes from one side of the hill to the other.

An experimental study of the stratified flow over triangular-shaped ridges of various aspect ratio revealed that wave amplitude can be maximized by 'tuning' the body shape or hill aspect ratio, $\alpha = W/h$, to the lee-wave field, Figure 31 (Castro *et al.*, 1983). In certain circumstances steady wave breaking can occur or multiple recirculation regions (rotors) can exist downstream, and that vortex shedding horizontal planes is possible even at $F = 0.3$. Significantly, it was found that hill shape and the ratio of the cross-stream width of the body to its height has a negligible effect on the dividing streamline height. As expected hill span affected upstream separation zones. The authors ended their paper with Scorer's (1978) warning: 'There is almost no systematic way of discussing the flow behind a three-dimensional obstacle of arbitrary shape when separation occurs!' Nonetheless, they felt certain generic phenomena could be studied and identified. Later Snyder *et al.* (1985) also studied the structure of strongly stratified flow over two- and three-dimensional hills. They concluded aspect ratio had small affect on the dividing streamline height. They also expressed concern that the upstream influence of stratified flow over long ridges takes so long to develop that it may be unlikely that stationary results can be obtained in finite length towing tanks. Snyder (1989) has also presented a summary of the various contributions made by the EPA Fluid Modeling Facility to a multi-year program known as the Complex Terrain Model Development Program (CTMDP).

### 5.4. Field/laboratory comparisons

As noted earlier Abe (1929) compared $CO_2$ streamline flows over a model of Mt. Fuji with cloud patterns in the atmosphere, and Long (1959) simulated mountain lee waves over the Sierra Nevada, California, using a brine filled water channel. Later Cermak and Peterka (1966) and Meroney and Cermak (1967) performed barostromatic[3] wind tunnel experiments over 1:12,000 scale models of Pt. Arguello, CA, and 1:6,200 scale models of San Nicolas Island, CA; however, only plume trajectories and concentrations were available for field/model comparisons. Kitabayashi *et al.* (1971) compared wind flow measurements over a 1:9600 scale model of Elk Mountain, WY, with extensive airplane soundings. Given rather coarse measurement resolution the two studies agreed quite well.

During a field and laboratory program to evaluate the efficacy of ground-based cloud seeding generators Orgill *et al.* (1971a, 1971b) made extensive measurements of wind flow, turbulence, temperature and dispersion over a scale models of the Eagle River Valley-Climax and the San Jan Mountain regions of Colorado. Both neutral and barostromatic boundary-layers were simulated over a 1:9600 scale model of the Eagle River/Climax area, Figure 32. Wind speeds and wind direction variations with height were measured using a novel stereo smoke-were method. Temperatures profiles were measured with thermocouples, and carbon dioxide and air density measurements were measured using thermal-conductivity cells. Concentrations from model plumes released at nuclei generator sites were determined using a Krypton-85 radioactive detector system.

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3 Airflow with stable thermal stability in the upper levels and near-neutral thermal stability in the lower levels.

Field data were taken during the winter snow season using rawindondes, pilot balloons, constant-volume balloon flights, aircraft and surface sampling of silver-iodide nuclei. Figure 33 compares the vertical rise or extent of the plume measured over the model during neutral and barostromatic simulations with field data. The barostromatic model simulated both the vertical and the lateral spread of the plume quite well. Model concentrations fell within the range of field surface concentration measurements. There was a great deal of scatter observed. but this was expected given the limited number of field measurements and the inherent variability of atmospheric turbulence. Both the laboratory and field data revealed that near-neutral stability conditions within the valley, orographically induced eddies, directional wind-shear and convection during the orographic storm events dispersed the seeding material in the vertical and cross-valley. Laboratory simulation despite its inherent limitations was found to be a practical tool for estimating airflow and dispersion characteristics over mountainous areas.

### 5.5. Conclusions from stratified airflow terrain studies

Physical modeling experience from studies performed over idealized two- and three-dimensional hills and scale models of complex actual complex terrain reveals:

- @ Dependent upon stratification, hill geometry and spacing various combinations of waves, downslope winds, valley penetration, streamwise division, upwind penetration and blocking can be reproduced in the laboratory,

- @ Hill top profiles of wind speed and turbulence are generally more dependent upon hill height than hill shape or aspect ratio,

- @ The dividing streamline concept works over a wide range of hill shapes and hill aspect ratios,

@ Two-dimensional ridges may block flow extremely far upwind,

@ Given two parallel ridges the largest downslope winds will occur on the second ridge,

@ Two dimensional ridges will generally produce larger vertical perturbations than three dimensional hills,

@ Undistorted models at scales as large as 1:10,000 permit resolution of velocity, turbulence and plume diffusion details,

@ With some effort studies of the effect of raised inversions and convective heating from below are possible, and

@ Careful tests over different models in different facilities produces equivalent results.

## 6. Drainage flow phenomena

Physical modelling of gravitational convection over complex terrain caused only by buoyancy forces requires the the model be isolated in a chamber free from other air disturbances. Cermak (1984) describes a convection chamber used to study mountain drainage flows and their influence on plume dispersion. A schematic of such a drainage flow facility is shown in Figure 34. The model must be constructed of a metal foil conductive surface to permit surface cooling by sublimation of dry ice or convection of cryogenic gases. Hertig (1986) argued that in the special case of drainage flows vertical geometric distortion justifies horizontal scales to 1:100,000 and vertical scales of 1:20,000. He constructed a scale model of Switzerland to simulate the hydrostatic contributions to the Föhn winds. Heating of the upper air temperature in a convection chamber produces a greater temperature potential and larger resultant flow velocities. Wind speeds are usually measured by visualization methods (*e.g.* smoke-wire).

Cermak and Petersen (1981) report the use of a convection chamber to study the drainage flows at two geothermal power plant sites in the Geysers Field of northern California and at a molybdenum mine site in the Rocky Mountains near Crested Butte, Colorado. An aluminum foil shell model was constructed at the molybdenum site of the surrounding Coal Creek canyon area. The 1:1,920 scale model was cooled by circulating gas cooled with two tons of dry ice placed in the insulated space below the model. Profiles of temperature and velocity measured over the mine site appear in Figure 35. Notice the up-valley recirculation which occurs at field heights above 500 m, the evidence of a mountain wind maximum at 150 m and the peak in valley drainage winds at about 60 m. The magnitude of the drainage winds was found to increase as the square root of distance from the canyon origin. Davidson and Rao (1963) observed a similar behavior during field observations. A few prototype measurements were made during drainage events in Coal Creek canyon, peak winds magnitudes found were about 5 m/s at 100 m. Model measurements at a similar location predicted wind speeds of 5.3 m/s at 125 to 150 m.

Limited data suggests that physical modeling of drainage flow can be achieved with sufficient accuracy to provide useful predictions of flow and dispersion; however, further evaluation and verification studies must be performed before the approach can be used with confidence.

## 7. Diffusion phenomena in complex terrain

Given accurate simulation of the dynamics and kinematics of flow over complex terrain there is good reason to expect similar simulation of the transport and dispersion of tracers or pollutants. Indeed in the absence of flow data over complex terrain similarity between field measurements of air pollution and model predictions is often used to validate numerical and physical model methodologies. Snyder (1981) considered the criteria and evidence for realistic air pollution simulation in his guideline manual for fluid modeling associated with the EPA Good Engineering Practice stack height regulations. Meroney (1986) extended this discussion to the criteria and evidence for fluid modeling of dense gas dispersion. Two studies have been selected to display the skills of fluid modeling while predicting dispersion over complex terrain.

A combined physical modeling and airborne monitoring study was performed near the Kingston Steam Plant (KSP), Tennessee, to evaluate the effects of terrain-induced turbulence and vertical velocity upon the plumes emitted from the plant (Graham *et al.*, 1978) The physical modeling tasks, conducted in the EWT at Colorado State University, included simulations both with and without local terrain features and for both short (100 m) and tall (300 m) stack configurations. Modeling techniques employed included flow visualization, gas tracer measurements and hot-wire anemometry. Airborne monitoring was conducting using a Cessna 207 aircraft equipped to measure wind speed, turbulence, temperature, humidity and concentrations.

The somewhat limited airborne data provided qualitative verification of the wind tunnel results. Both model and field produced turbulent intensities in the 0.1 range over the first 500 m above ground. Because model experiment were performed with and without underlying terrain it was possible to determine the effect of the terrain on ground level concentrations. Terrain effect were show to increase surface concentrations by a factor of two, Figure 36.

Liu and Lin (1975) simulated plume dispersion from a lead smelter in Glover, MO, over four terrain models with a 1:2,500 scale in a stratified towing tank. Figure 37 and Figure 38 show side and top view visualizations of buoyant stack plumes released into neutral ($Fr_H = U(NH)^{-1} = \infty$), slightly stable ($Fr_H$ = 5.4), and stable ($Fr_H$ = 2.7) conditions. Stack velocity ratio increases from $K = W_sU^{-1}$ = 1.4 to 4.4 as stability increases; however, plume buoyancy remains constant at $Fr_D \approx 3$, and plume rise stays nearly constant. Note that the rapid lateral and vertical spreading decreases as stability increases, but then, as the stratification increases further elevated waves induce local shear and the plume plunges toward the ground downwind of the mountains. Under neutral conditions, the plumes were considerably diluted within the simulated atmospheric boundary layer. Under stable conditions, the plumes were aloft upstream of the mountains, but high ground concentrations were measured in some cases downstream of the mountains at locations where downslope winds occur. Measurements of initial plume rise, $Z_T$, upwind of the mountain, Figure 39, agree with the prediction of Briggs (1969).

## 8. Summary

The last fifty years have seen a period of growth in the science of fluid modeling and its contribution to the understanding of atmospheric processes over mountainous terrain. The science has moved from ad hoc and intuitive experiments designed to provide engineering design answers to systematic fluid mechanic studies based on sound principles of fluid dynamics, similitude, and metrology. Broad insights gained through this half century of study indicate that:

@ The turbulent atmospheric boundary layer over complex terrain can be simulated in long test-section wind tunnels and water channels with the exception of effects caused by Coriolis accelerations,

@ The characteristics of wind speedup, lee waves, valley penetration, upwind columnar disturbances, and blocking have been simulated successfully in stratified wind tunnels and water channels,

@ Transport and diffusion over complex terrain for neutral and stratified flows has been successfully simulated in laboratory facilities, and

@ Laboratory results have been useful to guide the development of analytic and numerical models.

Nonetheless, much of wind engineering methodology is still more an art than a science; hence:

@ Further development of simulation methods for the convective boundary layer and elevated inversions is necessary,

@ Further attention should be directed to the lower critical Reynolds numbers required for correct simulation of neutral, stratified and drainage flow situations over complex terrain,

@ The value and validity of using vertically distorted complex terrain models to examine very large surface areas should be examined further, and

@ Consideration should be give to the value of using inverted topographical models with electrical heating for studies of drainage flows with nonuniform surface temperature distributions

Finally, new research areas for fluid modeling and complex terrain flows which should be fruitful include:

@ Research on the joint effects of surface heating, terrain shape, and raised inversion to evaluate their interactive nature,

@ Experiments to examine the sensitivity of drainage flow characteristics to upper air stability and weak synoptic winds, and

@ Systematic homogeneous and nonhomogeneous heating and roughness studies should be performed to act as a data base to guide the surface flux parameterization methods used in meso-scale numerical models.