Physical modeling of an outflow event in Howe Sound, British Columbia

Timothy D. Finnigan
Department of Civil Engineering, University of British Columbia, Vancouver, Canada

Susan E. Allen
Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, Canada

Gregory A. Lawrence
Department of Civil Engineering, University of British Columbia, Vancouver, Canada

Abstract. Outflow winds occur when differing air masses are separated by a coastal mountain barrier. In extreme cases the cross-barrier pressure gradient and the high degree of stratification (often approaching a distinct layered structure) result in channel winds which exhibit hydraulic features. We present a study of outflow winds in Howe Sound, British Columbia. A field investigation, aimed specifically at locating and quantifying hydraulic effects, was undertaken during the winter months of 1992/1993. Microbarographs positioned in the region recorded pressure changes at discrete locations in the streamwise direction. The pressures obtained during a severe outflow wind event, which occurred from December 27, 1992 to January 1, 1993, show a highly variable lower-layer depth suggestive of hydraulic control. Experiments were conducted with a three-dimensional physical model that is geometrically and kinematically similar to Howe Sound. Synoptic conditions recorded during the outflow wind event in Howe Sound in December 1992 were used to determine appropriate model flow forcing. The expanse of supercritical flow area was observed to be relatively sensitive to changes in along-channel pressure gradient and downstream depth, when compared to changes in discharge. Channel sinuosity and local topography appeared to force critical conditions at specific locations. For example, a channel bend combined with headlands was observed to force a situation where subcritical and supercritical streams flow side by side. Flow separation, resulting in lateral shear discontinuities, produced similar conditions. These effects are discussed and put into context with field observations. Field and model results show good agreement.

1. Introduction

Gap winds, first described by Reed [1931], are characterized by the flow of low-lying air through gaps in a mountain barrier when an across-barrier pressure gradient is present. Strong gap winds are often encountered in the valleys and inlets of coastal mountainous regions where cold weather is prevalent. During the winter months, the British Columbia coast (Figure 1) is geographically and climatically suited to extreme gap winds. Here such phenomena are referred to as outflow winds; a term which implies flow of air from the interior of the province out toward the coast.

The occurrence of an Arctic outbreak forces cold air south into the interior plateau region of the province, and the cold air, being relatively dense, deepens over a period of days becoming "pooled" between the Coast and Rocky Mountain ranges. The Coast mountains act as a partial barrier separating cold, dry interior air from warm Pacific air on the coast. The resulting across-barrier pressure gradient provides the driving force for outflow winds in valleys and inlets along the coast. The wind system is statically stable, but the degree of stratification depends on the local conditions present. In extreme cases the air masses differ substantially in their physical properties, and stratification is enhanced, often approaching a two-layer structure with a distinct and stable interface at the inversion level [Jackson, 1993].

The present study focuses on outflow winds that occur in Howe Sound, which is a fjord located in the southwest corner of the British Columbia mainland (see Figure 1). We present results from a field experiment, which captured a severe outflow wind event, and a laboratory experiment, designed to reveal the detailed structure of the wind system.

Howe Sound is typical of many fjords along the coast of British Columbia which also experience strong outflow winds during the winter months. The topography of the channel varies drastically over short distances. Rugged mountains interspersed along the channel give it a tortuous shape with many abrupt expansions and contractions. Steep mountain faces rise from the sea to heights of 1600 m in some parts of the Sound and combine with islands to influence and control the flow of air. Some important topographical features of Howe Sound are shown in Figure 2a, and the complexity of the terrain is shown in Figure 2b.

Outflow events in Howe Sound typically have durations as...
short as 8–10 hours but can last 4 to 5 days. Wind speeds commonly reach 20 m s\(^{-1}\) with gusts to 30 or 40 m s\(^{-1}\). The lower layer of cold air (wind layer) is generally less than 1000 m deep at all locations along the channel [Jackson, 1993]. On average, outflow winds occur on 4–5 days in each of December and January [Schaeffer, 1975].

Cold temperatures that accompany these winds and their unpredictability make them a serious hazard. Extreme wind conditions throughout the Sound during events are hazardous; however, the single, most dangerous aspect of outflow winds may be their spatial variability. The wind flows in a complicated layer through the channel. In several locations, velocities change abruptly over short distances. This is largely due to hydraulic effects (discussed below) and flow separation. Localized regions of very intense wind develop during an outflow event. Improvement of predictive capabilities for the above mentioned aspects of outflow winds was part of the motivation for this study.

Several gap wind studies have been conducted over the past 40 years with some researchers reporting flow features that resemble internal hydraulic jumps [Bond and Macklin, 1993; Lackmann and Overland, 1989]. Jackson and Steyn [1994a] compared observations of a moderate outflow event in Howe Sound with output from a three-dimensional mesoscale numerical model. Although their results agreed in general, model flows underestimated actual wind speeds in the channel, and small-scale flow features were not captured. Jackson and Steyn [1994a] suggested that the flow is strongly influenced by local topography, and a hydraulic analysis of their model output supported this. In a subsequent paper, Jackson and Steyn [1994b] described a one-dimensional hydraulic computer model that was more successful at predicting observations. Here they extended classical hydraulic theory by adding the influence of a synoptic pressure gradient in the form of a slope.

Finnigan et al. [1994] (hereinafter referred to as F1) presented results from a one-dimensional hydraulic physical model of outflow winds in Howe Sound. Model results were compared with observations from a severe outflow event in Howe Sound, which occurred in December 1992, and with output from Jackson and Steyn’s [1994b] hydraulic model. The paper identified the major topographical features that act as hydraulic controls. In a paper describing shallow water flow and vorticity production over isolated topography, Schär and Smith [1993] used one-dimensional hydraulic theory to help characterize different flow regimes. For subcritical upstream flow encountering a three-dimensional hill, the following three regimes occur: (1) fore-aft symmetry, essentially inviscid dynamics, and entirely subcritical conditions; (2) transition to supercritical flow and the occurrence of a hydraulic jump over the lee slope; and (3) the inability of the flow to climb the mountain top resulting in flow separation from the sides of the obstacle. These flow regimes have particular relevance to the...
study of outflow winds where an essentially shallow fluid encounters semi-isolated mountains and islands. Schär and Smith [1993] borrowed from the field of gas dynamics and drew an analogy with shallow water flow. Shear discontinuities and oblique shocks were identified as important features of flows described in their paper and may play a role in the spatial variation of outflow winds. A thorough summary of the theory of two-dimensional hydraulic jumps (and layered hydraulics in general) may be found in a recent book by Baines [1995].

The present paper reports measurements made in the field during a severe outflow wind event in Howe Sound. The field experiment was aimed specifically at capturing some of the hydraulic features of the strongly stratified system. Laboratory model experiments were performed for comparison with the field results and to specify conditions throughout the region in greater detail and for a wider range of possible flows.

Internal hydraulic theory refers specifically to the application of hydraulics in the study of the internal behavior in a multilayer system. In section 2, internal hydraulic theory, as it pertains to outflow winds, is briefly introduced. Field observations from an outflow event in December 1992 are discussed in section 3, and laboratory experiments are discussed in section 4. Comparisons between the field and laboratory results are made in section 5, and some conclusions are drawn in section 6.

2. Internal Hydraulic Theory

Single-layer hydraulic theory is useful for engineering applications in open channel flow [see Henderson, 1966]. For a single-layer flow the ratio of convective velocity $u$ to surface wave speed $c = (gh)^{1/2}$ is known as the Froude number

$$F = \frac{u}{\sqrt{gh}},$$

where $h$ is fluid depth, and $g$ is gravitational acceleration. Flow is termed subcritical when $F < 1$, critical when $F = 1$, and supercritical when $F > 1$.

In open channels, flow is controlled by channel features that determine a depth-discharge relationship [Henderson, 1966]. Such features (local contractions or changes in surface elevation) are called hydraulic controls, or simply controls, and the flow changes from subcritical to supercritical as it passes through them. At a control the flow is critical ($F = 1$). Transition from supercritical to subcritical flow occurs through a hydraulic jump. Enhanced turbulence intensity and energy loss accompany the hydraulic jump as the flow abruptly decreases in speed and increases in depth. Despite its simplicity, hydraulic theory is of great use in the study of channel flows as it retains the nonlinear advective term.

Extension to multiple fluid layers has made hydraulic theory useful in the study of geophysical flows. Outflow winds in Howe Sound are suitable for application of hydraulic theory since they are composed of a stratified two-layer system with a cold wind layer flowing beneath an essentially infinitely thick warm layer. The two layers are generally separated by a distinct interface in the form of an inversion. While there may be regions where the interface is relatively thick and fluid is exchanged between layers, it is reasonable and quite accurate to idealize the system, for analysis purposes, as two distinct layers [Jackson, 1993].

Hydraulic theory of layered flows makes the following assumptions: the fluids are inviscid, the pressure is hydrostatic, and within each layer, the density is constant and the velocity varies only in the flow direction. For a two-layer flow, Armi [1986] defined the composite Froude number

$$G^2 = F_1^2 + F_2^2 - eF_1^2F_2^2$$

where

$$F_n = \frac{u_n}{gh_n}, \quad n = 1, 2$$

are the densimetric Froude numbers for each layer; $g' = g(P_2 - P_1)/P_2$ is the reduced gravity; $h_n$ are the individual layer depths; and subscript 1 refers to the upper layer, while subscript 2 refers to the lower layer. The composite Froude number (2) determines the internal criticality of the two-layer flow in the same manner as the Froude number (1) determines the criticality of a single-layer flow.

More recently, Lawrence [1990] solved the hydraulic equations yielding characteristic velocities for both external (free surface) waves and internal (interfacial) waves. He derived exact expressions for internal and external Froude numbers based on the phase speed of infinitesimal long waves. From Lawrence's [1990] results, if we assume the relative density difference between layers is small (Boussinesq approximation), $\epsilon \ll 1$, then the internal Froude number for a two-layer flow is expressed as

$$F_I = \frac{u_2 - u_1}{(e'gh_1h_2(1 - F_2^2))^{1/2}},$$

where

$$F_2^2 = \frac{(u_2 - u_1)^2}{gh},$$

is the stability Froude number, and $h = h_1 + h_2$ is the total depth of fluid. When $F_2^2 > 1$, internal phase speeds are imaginary and internal hydraulic theory no longer applies. The internal Froude number also determines the internal criticality of two-layer flow by the criteria mentioned above for a single-layer flow.

The internal Froude number (4), which represents the ratio of internal convective velocity to internal phase speed, has the advantage of describing the behavior of oblique waves that appear in regions of internally supercritical flow. It is related to the composite Froude number by

$$F_I^2 = \frac{G^2 - F_2^2}{1 - F_2^2},$$

where the approximation is valid when $\epsilon \ll 1$. In the context of outflow winds the internal Froude number describes the hydraulic behavior of the wind layer [Finnigan, 1994]. If we assume the upper layer, $h_1 \gg h_2$ and therefore that $h \approx h_1$ then with $u_2 \gg u_1$ and $F_2^2 \to 0$, which is the case during outflow events, (4) reduces to

$$F_I \approx \frac{u_2}{(eg' h_2)^{1/3}},$$

which is exactly analogous to the single-layer Froude number (1) with $g$ replaced by $g'$. This means that the lower layer of the outflow wind system behaves hydraulically like a single layer of fluid reacting under a reduced gravitational field (i.e., $g'$). When the upper layer is much thicker than the lower
layer, the approximation (7) is valid and the upper layer thickness is unimportant. The simplification of (4) into (7) allows us to accurately model the two-layer wind system using a single layer of fluid. The methods used are discussed in section 4.

Following Lawrence's [1990] discussion, the external Froude number

\[ F_E \approx \frac{\bar{u}}{(gh)^{1/2}} \]  

where the flow weighted mean velocity \( \bar{u} = (u_1 h_1 + u_2 h_2) / h \). This Froude number, which is expectedly similar to that of single-layer flow, is of little significance in the outflow wind scenario since the upper layer is essentially infinitely thick and \( F_E \approx 0 \).

3. Field Experiment

Finnigan et al. [1994] discussed results from a one-dimensional laboratory model of outflow winds in Howe Sound. The initial modeling was followed by a field investigation conducted during the winter of 1992/1993. With some prior knowledge of the flow behavior (from the initial modeling) it was possible to strategically position microbarographs in Howe Sound at locations thought to be between control points and hydraulic jumps. The instruments recorded a severe outflow wind event that commenced on December 27, 1992, and continued until January 1, 1993. F1 presented cross sectionally averaged model results compared with microbarograph field data for this event. The field data were used to infer mean depth, velocity, and Froude number variation along the channel for two separate hydraulic regimes. Some of the flow features observed in the model were confirmed by the field data although the conclusions were mostly qualitative. Comparison of the results with a one-dimensional hydraulic computer model [Jackson and Steyn, 1994b] also showed positive agreement.

In section 3.1 we describe the synoptic conditions that led up to the December 1992 event. Following this, we introduce some additional data recorded during the December 1992 event at permanent weather stations in the Howe Sound region. These data are then used to reinterpret the microbarograph recordings, previously discussed by F1.


The evolution of synoptic-scale weather patterns creates the atmospheric boundary conditions within which outflow winds occur. The synoptic conditions in the December 1992 case are typical of other outflow wind cases [Jackson, 1993].

An upper level ridge, lying north-south across the Aleutian Islands (Figure 1), increased in amplitude during December 26–27, 1992. Meanwhile, an upper level cold low and an associated 998 mbar sea level low developed in a trough to the east and moved southward down the British Columbia coast to a quasi-stationary position 900 km southwest of Vancouver Island by 0400 PST, December 27. This pattern resulted in east to northeasterly flow aloft over the coastal zone. Linked with the upper level ridge, a 1060 mbar surface high-pressure zone, associated with very cold Arctic air, moved over Alaska and moved to a quasi-stationary position over central Yukon Territory by 0400 PST, December 27. Associated with these developments, an Arctic front moved southward across Howe Sound during the day on December 28. Behind the Arctic front, a zone of very large horizontal sea level pressure gradient, oriented perpendicular to the coast, resulted in strong low-level gap winds through the valleys and fjords dissecting the coast range. The strong pressure gradient and resulting winds began to weaken after December 29, when the upper level ridge-trough pattern decreased in amplitude, the Yukon high moved southeastward in British Columbia but weakened, and the Arctic front moved farther offshore.

3.2. Weather Station Data

As described by F1, the onset of outflow winds coincided with the occupation of Howe Sound by a shallow layer of relatively cold and dense air of interior origin. This occurred at approximately 1800 PST, December 27, 1992.

Hourly averaged data for wind speed (\( \bar{u} \)), temperature (\( T \)), and pressure (\( P \)) were obtained from three weather stations during the event. The stations were located at Pemberton (PM), Squamish (SQ), and Pam Rocks (PR). Data for potential temperature (\( \theta \)) was also obtained from a mountain station at Mount Strachan (MS). All stations are shown in Figure 2a with the exception of PM, which is located about 50 km upstream of SQ. SQ and PR are both located at approximately sea level, whereas MS is at an elevation of 1450 m, which is presumably above the inversion height.

Figure 3a shows the evolution of the pressure gradient (\( \partial P / \partial x \)) between PM and SQ, computed by simply taking the pressure difference between the stations divided by the distance separating them. Wind speeds recorded at SQ and PR are shown in Figure 3b where correlation with the pressure gradient is obvious. It is interesting to note that although PR is only 23 km downstream of SQ, wind speeds at PR are typically 2–3 times greater than at SQ throughout the event. This exemplifies the high streamwise variability of the flow and points toward some form of hydraulic control.

The ideal gas law was used to compute the fluid density at SQ and PR throughout the event. The results are shown in Figure 3c where it is evident that the flow consistently becomes less dense en route between SQ and PR.

Since only potential temperature data were available for MS (i.e., raw data for temperature and pressure, and therefore density, were not available), it was necessary to also compute \( \theta \) for SQ and PR in order to determine the reduced gravity \( g' \) at those locations (reduced gravity is computed here using \( g' = g(\theta_1 - \theta_2) / \theta_1 \) as opposed to the definition introduced in section 2). It was assumed that the upper layer potential temperature was a function of time but did not vary with location over the area of Howe Sound. Therefore the potential temperature at MS was used at both SQ and PR in the calculation of \( g' \). Potential temperature (referenced to sea level) is shown in Figure 3d. Relatively low temperatures recorded at SQ and PR confirm the presence of the wind layer flowing beneath the ambient warmer air (MS). The potential temperature difference between layers is nearly constant within the time frame of high-pressure gradients. The fact that PR has a consistently higher potential temperature than SQ may be a signature of some vigorous mixing process occurring somewhere between the two stations. We will show in the following sections that a complex flow with hydraulic jumps lies between the two stations and would likely cause significant entrainment of warmer fluid from above into the lower layer. This is consistent with the density variations shown in Figure 3c.

Temporal variation of reduced gravity is shown in Figure 3e. As the cold air invades Howe Sound and the potential tem-
temperature in the lower layer decreases (hour 15-60), independently of the upper layer, $g'$ shows a marked increase at both locations. High values of $g'$ persist until approximately hour 110 when the event begins to subside.

### 3.3. Microbarograph Data

The locations of the microbarographs are shown in Figure 2a as black dots numbered 1–5 in the direction of flow. An effort was made to place the instruments at shore locations, which were not immediately below valley walls. Ideally, all of the instruments would be placed roughly along the centerline of the valley. All of the instruments were close to sea level, and estimates of their elevations ($z$) are given in Table 1. The microbarographs continually recorded pressure at the five stations from December 1992 to February 1993. Here we present results for five days corresponding to the weather station data described above.

Pressure variation at each station for the duration of the event is shown in Figure 4. Prior to the onset of strong winds the pressure recordings at each station roughly coincided (up to about hour 14), indicating an almost uniform synoptic pressure distribution over the 50 km span of the instruments.

When the cold interior air occupied the lower elevations of the region, the gravitational response of this wind layer to the drastic topography of Howe Sound caused its depth to vary significantly in the flow direction. Depth variation may be due to a combination of simple mass conservation, hydraulic control, and interfacial waves.

Beginning at approximately hour 14, the wind layer developed rapidly, and depth differences between stations are reflected in the separation of the pressure lines (although all stations still follow the synoptic trend). Note that this coincides with the rapid increase in pressure gradient as shown in Figure 3a. Microbarograph data at stations 3 and 4 between hour 29 and 47 were lost due to instrument failures. Dashed lines indicate sections of lost data, and it is apparent that the wind layer changed significantly during this time.

### 4. Laboratory Experiments

#### 4.1. Description

Finnigan et al. [1994] presented results from a physical model whose dimensions varied only in one direction. For this reason it may be referred to as a one-dimensional model (even though the flow is at least two-dimensional). The model described there was designed by using estimates of the average channel width at several locations along the east channel of Howe Sound. The channel was effectively closed along the west side by assuming a wall roughly aligned with Anvil, Gambier, and Bowen Islands (see Figure 2). In the resulting model...

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**Table 1.** Estimated Elevation, Above Mean Sea Level, of Microbarograph Instruments Positioned in Howe Sound During the December 1992 Outflow Wind Event

<table>
<thead>
<tr>
<th>Station</th>
<th>Elevation, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Exact elevation measurements were not possible.
flows, velocity and depth were assumed to vary only in the flow direction.

While the F1 model was successful in predicting the basic hydraulic behavior of the wind system, it was limited in its resolution and accuracy. The results were particularly useful in determining appropriate locations to situate instruments in the field.

The physical model described in the present paper has dimensions varying in all three coordinate directions. The model includes the following, which were not considered in the previous model study reported by Fin: (1) correct simulation of boundary conditions; (2) effects due to channel sinuosity and elevation changes; (3) flow over and around, and effects due to, islands in the channel; (4) variation in wind across as well as along the channel; (5) energy losses due to form drag and skin friction drag; (6) more accurate similarity; and (7) simulated pressure gradients.

In the field the Coriolis force is associated with a small change in the height of the interface across the valley. Taking rough estimates of the channel width $W$, the flow velocity $U$, the Coriolis parameter $f$, and $g^*$, we may estimate the tilt as $\Delta \eta = \frac{WfU}{g^*} = \left(8000 \text{ m}\right) \left(10^{-4} \text{ s}^{-1}\right) \left(12 \text{ ms}^{-1}\right) / (0.4 \text{ ms}^{-2}) = 24 \text{ m}$, which is quite insignificant relative to the undulations in the interface observed in the model flows (~500 m). Rotation was therefore not included in the model study.

The topography of the Howe Sound region was reproduced and extended in the upstream and downstream directions to minimize boundary effects. The model is shown in Figure 5 which is the view up the channel from the downstream end. This model was produced by replicating each 150 m contour level from contour maps of the Howe Sound area. The levels were built up by sequentially stacking sheets of cork material (~5 mm thick), each cut to the shape of a single contour level. The steps in between contours were then filled by hand resulting in a model which resolves map detail to a resolution of 150 m in the vertical.

In the upstream direction the model extends to the nearest large reservoir of cold air that exists in the field (Pemberton Valley). By making this extension the inflow conditions are properly simulated. In the downstream direction the model extends approximately 10 km into the Strait of Georgia.

A single layer of water was used to simulate the lower (wind) layer of the actual two-layer system. By omitting an upper layer in the model, mixing and friction between layers were ignored. Mixing of upper layer fluid likely occurs in the field which may affect the buoyancy of the lower layer and modify the dynamics slightly from what we see in the model. As far as friction is concerned, since the velocity in the upper layer is small, the frictional drag at the interface between the two layers is relatively small compared to the surface drag (Turner, 1973, p. 184). Therefore surface friction was modeled by applying surface roughness elements to the land and water areas of the model. The element size and spacing, representing the actual terrain, were determined through energy considerations and scaling laws (Chow, 1959).

In the model, water enters over a weir at the upstream end (see Figure 5) and flows through the model terrain to a weir, beyond the downstream channel terminus, which establishes the downstream depth $h_d$ (or ambient inversion height).

Representative model flows are based on the constancy of Froude number between the model and the field flows. The model Froude number has the single-layer form of equation (1) and the field Froude number (7) is that for two-layer flow.
with an infinite, slow-moving upper layer. Froude number similarity is achieved by equating (1) and (7) which leads to

$$\frac{u_f}{u_m} = \left( \frac{h_f}{h_m} \right)^{1/2}$$

where subscript \( m \) refers to model and subscript \( f \) refers to field. If the ratio of field to model quantities is indicated by subscript \( r \), then (9) becomes

$$u_r = (e h_r)^{1/2},$$

where \( e \) must be estimated or known from field observations. With knowledge of model and field dimensions, (10) can be used to derive expressions for scale ratios for several quantities such as total discharge \( Q \).

The model was designed to produce flows having Reynolds number, \( Re = \frac{u_m h_m}{\nu} \), large enough everywhere that viscous effects are insignificant, as they are in the field (\( \nu \) is the dynamic viscosity of water at the laboratory temperature). This condition was achieved through a slight vertical distortion of the model which effectively increased the fluid depth (and Reynolds number) while maintaining geometric and kinematic similarity with the field (full dynamic similarity is impossible since it requires \( Re_m = Re_f \)). With \( L_r \), representing the ratio of horizontal distances a vertical distortion factor may be defined by

$$e = \frac{h_r}{h_m},$$

which is equal to the ratio of slopes \( S_r \) and is usually \( \leq 1 \). The model described here has \( L_r = 48,000 \) and \( h_r = 27,500 \) and therefore a distortion factor of \( e = 0.57 \) which is well above the acceptable lower limit of 0.25, as suggested by Nicollet [1989]. The actual dimensions of the model are approximately 3.5 m in the streamwise direction and 1 m in the cross-stream direction.

To simulate synoptic pressure gradients, an equivalent gravitational force was imposed by sloping the model along the channel axis. The pressure gradient in the field, \( \frac{dP}{dx} \), may be expressed as slope

$$S_t = (g' \rho)^{-1} \frac{dP}{dx},$$

which is positive for increasing pressure along the channel axis in the downstream, or positive \( x \) direction. As stated above, the distortion coefficient is equal to the ratio of slopes; that is, \( e = S_r = S_t/S_m \). Therefore using observed values of the quantities in (12), we were able to predict a range of suitable model slopes to simulate pressure gradients likely to be encountered.

### 4.2. Data Acquisition

Video and image analysis techniques were used to obtain flow data. Velocity and depth values, which together give the Froude number using (1), were obtained at the intersections of a 2 cm \( \times \) 2 cm grid covering the model flow domain. Velocity and depth data, for each model run, were recorded separately by a mobile video system mounted above the model. Individual frames from the recorded video were analyzed by using a computer to extract data values at the desired points. A vertical light sheet was used to illuminate cross sections in the flow to allow depth measurement, and flow was seeded with plastic particles (1 mm diameter) to produce streaks which were converted to velocity values. To eliminate time-dependent noise and obtain adequate overall particle density, several source images were acquired at each location, and multiple measurements were averaged to produce each data value (refer to Finnigan [1994] for further details).

### 4.3. Results

Results were obtained for eight different flows, each simulating outflow winds under a different set of synoptic conditions expected in the field. Velocity, depth, and Froude number, for each flow, reveal the subcritical and supercritical regions and some of the dynamic features present in the wind layer. The model flows were based on synoptic conditions present in Howe Sound during December 1992, described above and previously reported by F1.

#### 4.3.1. Governing parameters.

Aside from model slope (described above) the other two parameters which determine a model flow are total discharge \( Q \) and downstream depth (inversion height) \( h_d \). Estimates of these two parameters were made by conducting several preliminary experiments to determine which gave reasonable results (in comparison with previous observations made by Jackson and Steyn [1994a]).

Two values for each of the three model parameters were used (see Table 2). All possible combinations of these values were used resulting in \( 2^3 = 8 \) cases. Table 3 outlines the parameter settings for each case and lists some physical characteristics, in field dimensions, from the results. The overall effect of each parameter on the wind system is suggested by these results.

Referring to Table 3, it is apparent that the expanse of supercritical flow (column 5) is governed mainly by \( h_d \) and \( dP/dx \). The coupled effect of these parameters is reflected in a positive influence by \( dP/dx \) and a negative influence by \( h_d \). The discharge \( Q \) has a lesser effect, and its influence seems to depend on the other parameters. These relationships are depicted in Figure 6, where the solid lines are not intended to show any intermediate trend but simply connect points with corresponding values of \( h_d \).

#### 4.3.2. Topographical influence.

As described in section 4.1, the data acquired from the model provide the conditions throughout Howe Sound. Although velocities may be largely three-dimensional in some locations, we are concerned with horizontal variations on a relatively large scale and have therefore presented only the horizontal component of the depth-averaged velocity. It is the hydraulic behavior of the wind system that is of primary interest.

Results are referred graphically to the Howe Sound region.

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**Table 2. Model Parameters and Corresponding Values in Field Dimensions**

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Discharge, m³ s⁻¹</th>
<th>Weir Height, mm</th>
<th>Model Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low (L)</strong></td>
<td>3.8 \times 10⁻⁴</td>
<td>32</td>
<td>0.039</td>
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<tr>
<td><strong>High (H)</strong></td>
<td>5.7 \times 10⁻⁴</td>
<td>41</td>
<td>0.053</td>
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</table>

<table>
<thead>
<tr>
<th>Corresponding Field Values</th>
<th>Discharge, m³ s⁻¹</th>
<th>Inversion Height, m</th>
<th>Pressure Gradient, Pa m⁻¹</th>
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<tbody>
<tr>
<td><strong>Low (L)</strong></td>
<td>1.7 \times 10⁻¹</td>
<td>960</td>
<td>-0.015</td>
</tr>
<tr>
<td><strong>High (H)</strong></td>
<td>2.6 \times 10⁻¹</td>
<td>1200</td>
<td>-0.020</td>
</tr>
</tbody>
</table>

The following values were used: \( g' \), 0.51 ms⁻¹; density, 1.31 kg m⁻³.
Table 3. Model Parameter Settings and Some Important Physical Aspects of Results for Eight Simulated Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Settings</th>
<th>Maximum Velocity, m/s</th>
<th>Maximum Depth, m</th>
<th>Maximum Froude Number</th>
<th>Total Supercritical Area, km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L, L, L</td>
<td>22.6</td>
<td>833</td>
<td>3.6</td>
<td>116</td>
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<td>2</td>
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<td>123</td>
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<tr>
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<tr>
<td>5</td>
<td>L, H, L</td>
<td>16.8</td>
<td>1151</td>
<td>4.9</td>
<td>41</td>
</tr>
<tr>
<td>6</td>
<td>H, H, L</td>
<td>19.8</td>
<td>1148</td>
<td>5.3</td>
<td>53</td>
</tr>
<tr>
<td>7</td>
<td>H, H, H</td>
<td>25.8</td>
<td>1031</td>
<td>6.3</td>
<td>162</td>
</tr>
<tr>
<td>8</td>
<td>L, H, H</td>
<td>24.4</td>
<td>975</td>
<td>5.6</td>
<td>178</td>
</tr>
</tbody>
</table>

L refers to the lower setting and H to the higher. The sensitivity to each controlling parameter may be observed by comparing the following pairs of cases: Q (1 versus 2, 3 versus 4, 5 versus 6, 7 versus 8), h_d (1 versus 5, 2 versus 6, 3 versus 7, 4 versus 8), dP/dx (1 versus 4, 2 versus 3, 5 versus 8, 6 versus 7). Results are presented in field dimensions.

as pictured in Figure 2a. This reference figure may be used to identify locations and geographical features that appear in the results of Figures 7-14, which are not extensively labeled to avoid clutter. The spatial dimensions in Figure 2 provide a coordinate system for reference, and the topography of the area can be clearly seen. The results appear, for the eight cases modeled, in Figures 7 through 14.

The hydraulics of three-dimensional flow differs in nature from the simple, cross sectionally averaged, one-dimensional flow case. Schär and Smith [1993] investigated the hydraulic structure of flows encountering topography and characterized some important features. In the case of a complicated channel like Howe Sound, such features as controls and hydraulic jumps are not likely to span the entire width of the channel wherever they occur. Often a portion of the flow width will be controlled, while a region alongside it is not. A supercritical region may be flanked on one or both sides by regions of subcritical flow. The lateral boundary between two flows of different criticality may be termed a shear discontinuity since the flow will have different depth, speed, and possibly direction on either side. Oblique shocks may form where supercritical flow encounters an obstruction which alters the flow direction.

In some cases the flow may only pass through a weak shock and still remain supercritical, although at lower Froude number on the downstream side.

We now discuss the results for each modeled case individually. Case 1 is typical of a moderate outflow wind event and

Figure 6. Effect of individual model parameters on supercritical flow area. For the selected values, as shown in Table 3, changes in dP/dx and h_d significantly influence the expanse of supercritical flow, while Q does not. The solid lines are not intended to show any intermediate trend but simply connect points with corresponding values of h_d.

Figure 7. Case 1: Q = L, h_d = L, dP/dx = L. (a) Depth section along channel axis. The line along which the data were extracted is shown as a grey line in Figure 7b. (b) Velocity (as arrows) and critical Froude number (F = 1) distribution (contoured). Velocities less than 1 m s⁻¹ not shown. The contours enclose regions of supercritical flow with the upstream portion of the contour itself indicating the location of a control. The downstream portion of the contour represents a hydraulic jump and the side portions indicate either a physical boundary or a lateral flow discontinuity. (c) Photograph of the model flow from above. Pearlescence particles have been added to the water. This and subsequent figures presented in field dimensions. A separation point (number 1) shear discontinuity (2), oblique hydraulic jump (3), and two-dimensional hydraulic jump with shear lines (4, 5) are shown in Figure 7c.
Figure 8. Case 2: $Q = H, h_d = L, \frac{dP}{dx} = L$. (a) Depth section along channel axis. (b) Velocity and critical Froude number ($F = 1$) distribution. (c) Photograph of the model flow from above.

Figure 10. Case 4: $Q = L, h_d = L, \frac{dP}{dx} = H$. (a) Depth section along channel axis. (b) Velocity and critical Froude number ($F = 1$) distribution. (c) Photograph of the model flow from above.

Figure 9. Case 3: $Q = H, h_d = L, \frac{dP}{dx} = H$. (a) Depth section along channel axis. (b) Velocity and critical Froude number ($F = 1$) distribution. (c) Photograph of the model flow from above.

Figure 11. Case 5: $Q = L, h_d = H, \frac{dP}{dx} = L$. (a) Depth section along channel axis. (b) Velocity and critical Froude number ($F = 1$) distribution. (c) Photograph of the model flow from above.

exhibits many hydraulic features common to subsequent cases. The occurrence and location of hydraulic controls and jumps in the wind layer agree generally with the results presented by Fl. We focus our discussion of the flow field in case 1 and then extrapolate to briefly describe the other cases in comparison. Specific locations in results figures will be referred to by $(x, y)$ coordinates (panels b and c in each figure) where along-channel distance increases in the flow direction.
critical flow. The flow is controlled by the promontory near (10, 18) but only across a portion of the channel. Here the control occurs due to flow over an obstacle which spans only part of the channel. The sharp bend in the channel at this location and relatively steep walls on the opposite side combine with the promontory to produce a complicated flow pattern with a deep recirculating flow (not apparent in the figure but observed) existing next to a region of supercritical flow. A hydraulic jump occurs on the lee side of the promontory.

The flow is again controlled, this time across the entire channel, by the contraction near (10, 23). As the flow separates from the west side of the Sound near (8, 27) it remains supercritical for some distance while flowing alongside the subcritical entrance to the west channel of the Sound. The location of the separation point is shown by arrow 1 in Figure 7c. Here the supercritical flow (moving faster than the surface wave speed) has no indication of the abrupt widening and bifurcation of the channel. The subcritical side channel becomes its lateral boundary in the form of a shear discontinuity.

Anvil Island appears perfectly located to deflect almost all of the flow down the east channel. However, the deflection does not occur efficiently as flow tends to be blocked by Anvil Island and is forced through a strong hydraulic jump near (10, 33). Note the relative depth of this hydraulic jump as shown in Figure 7a. The partial blocking by the channel contraction imposed by Anvil Island is analogous to the well-known choking condition for supercritical flow [Henderson, 1966, pp. 248–249]. The abrupt widening of the channel near (10, 27) possibly acts in combination with upstream blocking from Anvil Island to cause the hydraulic jump in this case. Some direct evidence for the occurrence of this jump was found in the field recordings [Finnigan, 1994].

Following the hydraulic jump described above, the flow is

Figure 12. Case 6: \( Q = H, h_d = H, dP/dx = L \). (a) Depth section along channel axis. (b) Velocity and critical Froude number \( (F = 1) \) distribution. (c) Photograph of the model flow from above.

4.3.2.1. Case 1 \( (Q = L, h_d = L, dP/dx = L) \) (Figure 7): Although mostly subcritical, the upstream region of the channel near Squamish (11, 15) is hydraulically controlled by local elevation changes resulting in small patches of weakly super-

Figure 13. Case 7: \( Q = H, h_d = H, dP/dx = H \). (a) Depth section along channel axis. (b) Velocity and critical Froude number \( (F = 1) \) distribution. (c) Photograph of the model flow from above.

Figure 14. Case 8: \( Q = L, h_d = H, dP/dx = H \). (a) Depth section along channel axis. (b) Velocity and critical Froude number \( (F = 1) \) distribution. (c) Photograph of the model flow from above.
immediately controlled by the throat between Anvil Island and the east side of the channel. The supercritical stream separates from the trailing edge of Anvil Island forming a lateral shear discontinuity. This feature can be seen in Figure 7c at arrow 2.

As was proposed by Jackson [1993], the flow is largely confined to the east channel by the islands (Anvil, Gambier, Bowen) forming a large supercritical region (see Figure 7b). A complicated oblique shock occurs near (15, 44) across the entire east channel (Figure 7c, arrow 3). This is clearly seen in the data as the $F = 1$ line departs from the east side of the channel at an angle. Some slight differences are apparent between the exact location of shock lines in Figure 7c and the $F = 1$ contours in Figure 7b. This is due to the interpolation between the discrete data points.

On the opposite side of the east channel the jump formation is more complicated. Just upstream of Bowen Island, it appears that part of the subcritical stream (on the west side of the shear discontinuity (2)) is controlled by a small protrusion of Gambier Island near (11, 40). This appears in Figure 7b as a westward extension of the $F = 1$ contour. The criticality of this stream is not the same as that of the flow to its left (subcritical) or to its right (supercritical). Here the flow is laterally discontinuous along two shear lines, shown by arrows 4 and 5 in Figure 7c. However, both supercritical streams revert to subcritical flow within the same hydraulic jump (14, 44).

Energy is dissipated, downstream of the hydraulic jump, by intense turbulence which is advected downstream in a well-defined jet. The energetic subcritical jet extends almost uninterrupted through the channel exit region and into the Strait of Georgia. It should be noted that momentum combined with the synoptic pressure gradient carries cold air from this jet over the Strait, where it accumulates moisture. This is commonly observed to result in snow belts along the east coast of southern Vancouver Island (see Figure 1).

At the channel exit, part of the jet overtops the headlands near (17, 48) and is locally controlled but reverts to subcritical conditions through a hydraulic jump on the lee of the obstacle.

It is interesting to note the presence of oblique waves that form in supercritical regions (slightly visible in Figure 7c) at an angle with the side walls given by $\sin^{-1}(1/F)$. Such waves have been observed in layered supercritical geophysical flows [see Farmer and Armi, 1986].

4.3.2.2. Case 2 ($Q = H$, $h_d = L$, $dP/dx = L$ (Figure 8)):

The increase in discharge, from that for case 1, increases the depth of flow. Although it seems to decrease the supercritical region near the channel exit (17, 48), it has an overall effect of increasing the expanse of supercritical flow. The deeper flow is now able to go over rather than around larger portions of Gambier and Bowen Islands and is controlled as it does so. Small velocities downstream of the hydraulic jump near (16, 45), combined with a greater fluid depth, limit the size of the supercritical area near (17, 48).

4.3.2.3. Case 3 ($Q = H$, $h_d = L$, $dP/dx = H$ (Figure 9)):

The increase in pressure gradient causes a substantial increase in supercritical flow. The supercritical region near (12, 18), however, seems fixed in size as a hydraulic jump is forced on the lee side of the promontory. A large supercritical region now spans most of the length of the lower channel, extending out beyond the terminus before reverting to subcritical conditions through an apparent undulating hydraulic jump. Although the flow is substantially blocked by Anvil Island, resulting in a hydraulic jump that tends to "pile" fluid up against the steep slopes of the island, it remains supercritical through part of the channel.

Downstream, the flow now has enough energy to pass over the eastern part of Gambier Island, resulting in significantly higher velocities in the central part of Howe Sound. A weak oblique shock appears to form from both sides of the east channel near (15, 48), and the data suggest that the flow remains supercritical on the downstream side. A strong hydraulic jump forms over the north end of Bowen Island (11, 48) and into the central part of the Sound. A supercritical region forms as fluid is forced through a valley on the south side of Bowen Island near (10, 52). The onset of this condition would not be welcomed by the residents of the area (Bowen Island is well populated).

4.3.2.4. Case 4 ($Q = L$, $h_d = L$, $dP/dx = H$ (Figure 10)):

As expected, a decrease in discharge causes only minor changes to the flow compared to the previous case. The undulating hydraulic jump does not form, and the region of supercritical flow is slightly smaller.

4.3.2.5. Case 5 ($Q = L$, $h_d = H$, $dP/dx = L$ (Figure 11)):

This combination produces a flow pattern different from those discussed above. The flow is substantially deeper and slower and although Anvil Island directs the flow into the east channel, the other islands do not confine it. The flow subcritically separates from the east side of the channel (12, 32) and proceeds in a direct path over the islands toward the Strait of Georgia. The subcritical separation does not result in a shear discontinuity which only occurs in supercritical flow. In the separated region (16, 40) a slow-moving counterclockwise eddy is formed.

4.3.2.6. Case 6 ($Q = H$, $h_d = H$, $dP/dx = L$ (Figure 12)):

The increase in discharge from the previous case delays the separation from the eastern side of the channel. The flow is again confined mainly to the east channel and a small separated region exists near (16, 40). Relative to the first four cases the flow is slow and deep, and although supercritical regions near (13, 28) and (12, 37) are present, the supercritical downstream region (12, 37) is somewhat smaller than the first four cases. This and the previous case typify conditions expected for low-pressure gradient forcing with a relatively high inversion level.

4.3.2.7. Case 7 ($Q = H$, $h_d = H$, $dP/dx = H$ (Figure 13)):

This case is similar to that of cases 1 and 2 but is characteristic of a stronger flow with a larger area occupied by supercritical flow. The three prominent regions of supercritical flow are again present but are slightly larger. As well, the laterally discontinuous supercritical region (centered near (10, 40)), as described above for case 1, is present.

4.3.2.8. Case 8 ($Q = L$, $h_d = H$, $dP/dx = H$ (Figure 14)):

The change in discharge has the opposite effect in this strong flow case as it did in the moderate flow cases 1 and 2. With high forcing, the response to a decrease in discharge is an increase in the amount of supercritical flow area. Controls occur farther upstream due to the decrease in depth that accompanies a decrease in discharge. The two main downstream supercritical regions have joined as in cases 3 and 4. This occurs despite some flow blocking upstream of Anvil Island. A hydraulic jump limits the extent of this region and it does not extend out of the channel as in cases 3 and 4.

5. Comparison of Field and Model Results

5.1. Pressure Comparison

To evaluate the ability of the physical model to represent real flows, we present a comparison between the laboratory
and the field data. The pressure gradient present in the field was simulated by the tilt of the model in the lab, as explained in section 4. The slope of the physical model $S_m$ necessary to represent a pressure gradient in the field ($dP/dx_f$) is

$$S_m = (e \rho_f g'_f)^{-1} (dP/dx_f), \quad (13)$$

where $e$ is the distortion of the model and $\rho_f$ and $g'_f$ are the density and reduced gravity in the field, respectively.

For comparison between the model results and the field results it is necessary to choose times in the field results when the pressure gradient, density, and reduced gravity give one of the two slopes used in the lab. The pressure gradient values represented by the two slopes (0.039 and 0.053) in the lab are given in Table 2 for $g' = 0.51 \text{ m s}^{-1}$ and $\rho_f = 1.31 \text{ kg m}^{-3}$. Matching slopes and pressure gradients is complicated by the fact that $S_m$ is a function of $\rho_f$ and $g'_f$ as well as the pressure gradient. Calculations show that the two slopes used in the lab each match pressure gradients in the field twice. The first two matches occur in the initial development phase of the event at about hour 10 and hour 15 for the low and high slope, respectively. The second match for the high slope unfortunately occurs at about hour 45 when data were lost from two of the sensors. Thus a comparison is made between the low slope laboratory data and the field data at its second match, at hour 15. The agreement between case 6 and the field observations is fairly good. It is interesting to note that this occurs despite the mixing (not modeled) which must occur between Squamish and Porteau Rocks as witnessed by the change in density and reduced gravity. Further laboratory experiments are under way in order to allow comparison to more of the data record and to the wind speeds from the field for case 6, taken from locations closest to SQ and PR and converted to field dimensions, are shown in Figure 17 along with field values at hour 57 (see Figure 3b). The straight line in the figure would be one-to-one correspondence. Case 6 gives a good approximation of the observed wind velocity at Pam Rocks. However, it overpredicts the velocity at SQ perhaps due to sheltering of the anemometer at SQ.

The agreement between case 6 and the field observations is fairly good. It is interesting to note that this occurs despite the mixing (not modeled) which must occur between Squamish and Porteau Rocks as witnessed by the change in density and reduced gravity. Further laboratory experiments are under way in order to allow comparison to more of the data record and to data from Jackson and Steyn [1994a].

6. Discussion and Conclusions

Microbarograph pressure recordings showed that the outflow wind event, which occurred in Howe Sound during December 1992, exhibited large spatial variability. Comparison between the field and the model results for matching average $dP/dx$ allowed a more thorough description of the along-channel behavior. By producing a range of model flows we were able to span most of the field results and achieve a reasonable agreement. One flow period was identified during which the along-channel depth variation was nearly constant. Very close agreement was found between the field results at hour 57 and the model values from case 6. The other model

Table 4. Values of Observed Quantities at Hour 57

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synoptic pressure gradient, $dP/dx_f = (\text{Pa m}^{-1})$</td>
<td>-0.016</td>
</tr>
<tr>
<td>Wind speed (SQ), $u_x = (\text{m s}^{-1})$</td>
<td>8.5</td>
</tr>
<tr>
<td>Wind speed (PR), $u_x = (\text{m s}^{-1})$</td>
<td>24.3</td>
</tr>
<tr>
<td>Reduced gravity (SQ), $g' = (\text{m s}^{-2})$</td>
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</tr>
<tr>
<td>Reduced gravity (PR), $g' = (\text{m s}^{-2})$</td>
<td>0.42</td>
</tr>
<tr>
<td>Reduced gravity, average, $g' = (\text{m s}^{-2})$</td>
<td>0.51</td>
</tr>
<tr>
<td>Lower layer density (SQ), $\rho_f = (\text{kg m}^{-3})$</td>
<td>1.33</td>
</tr>
<tr>
<td>Lower layer density (PR), $\rho_f = (\text{kg m}^{-3})$</td>
<td>1.30</td>
</tr>
<tr>
<td>Lower layer density, average, $\rho_f = (\text{kg m}^{-3})$</td>
<td>1.31</td>
</tr>
<tr>
<td>Difference in pressure, stations 2-1, $dP_f = (\text{Pa})$</td>
<td>233</td>
</tr>
<tr>
<td>Difference in pressure, stations 3-1, $dP_f = (\text{Pa})$</td>
<td>245</td>
</tr>
<tr>
<td>Difference in pressure, stations 4-1, $dP_f = (\text{Pa})$</td>
<td>448</td>
</tr>
<tr>
<td>Difference in pressure, stations 5-1, $dP_f = (\text{Pa})$</td>
<td>467</td>
</tr>
</tbody>
</table>

The average values of reduced gravity and density were used to scale-up from model results.

![Figure 15. Comparison of field measurements (diamonds) with case 6 laboratory measurements of $\Delta P$ as a function of distance along the channel. The error bars reflect uncertainty in scaling of the laboratory measurements to field results.](image-url)
cases may occur in nature under different synoptic conditions from what were present during the December 1992 event.

In general, the physical model shows a highly variable flow field under different forcing and boundary conditions. The expanse of supercritical flow is found to vary substantially in response to a changing pressure gradient. This fact is important in practical considerations since the growth of a supercritical region could be predicted by forecasting the pressure gradient in the field.

As conditions change, the flow regime may change in localized areas between the three regimes discussed by Schar and Smith [1993]. In particular, it is evident from model results that the flow may or may not be confined to the eastern channel of Howe Sound. In the cases that it is confined (cases 1, 2, 3, 4, 7, 8), flow separation occurs downstream of topography resulting in shear discontinuities with subcritical flow in the lee of the obstruction alongside supercritical flow in the east channel. This situation is well known to ferry operators who traverse lower Howe Sound regularly, even in extreme winds (C. Whalin, personal communication, 1993). On several occasions, in particular during the December 1992 event, the operator reported that intense winds sharply decreased as the ship moved from the east channel to the passage between Gambier and Bowen Islands (i.e., across a shear discontinuity from supercritical to subcritical flow).

In some cases, such as that for model cases 5 and 6, the wind layer is deep enough and has enough energy to overtop the islands. In these cases the flow is primarily subcritical in the vicinity of the islands which tend to cause undulations on the interface downstream. These cases could be important in the generation of large-amplitude internal waves at the inversion height.

The results presented suggest that the physical model is capable of providing insight into the complicated dynamics of outflow winds in Howe Sound. Since these winds occur infrequently and are difficult to predict, they constitute a system that is quite difficult to study using field measurements alone. Available data are generally limited to discrete locations. Therefore the high spatial variability of the winds is not resolved well by stationary weather stations. The model has allowed us to reveal some of the complicated flow structures and hydraulic effects that characterize these flows. Comparisons with field data have allowed an analysis of trends and causes of certain flow phenomena, such as hydraulic jumps. Future uses of the model may involve extending the parameter range and making further comparisons with a data set acquired by Jackson and Steyn [1994a].

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S. E. Allen, Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, B. C., Canada.

T. D. Finnigan, Centre for Water Research, University of Western Australia, Nedlands, Perth WA 6907, Australia. (e-mail: finnigan@cwr.uwa.edu.au)

G. A. Lawrence, Department of Civil Engineering, University of British Columbia, Vancouver, B. C., Canada.

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