The Influence of Wind on the Surface Layer of a Stratified Inlet: Part I. Observations

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ABSTRACT

Observations are described in an experiment undertaken to determine the response of a stratified inlet to changing conditions of wind, tide and runoff. Time series of conductivity profiles taken in Alberni Inlet, British Columbia, show marked fluctuations in surface layer thickness that appear to be related to strong winds. The effect of an up-inlet wind is to produce a rapid thickening of the fresh-water layer at the inlet head which may persist for several days. Strong winds were also associated with significant changes in the intensity of stratification.

1. Introduction

This paper describes an experiment to determine the time-dependent effects of wind on the surface waters of Alberni Inlet. In common with many other inlets of the Pacific Northwest, Alberni Inlet has a thin (~3 m), comparatively fresh layer overlying water of nearly oceanic salinity. The strong vertical salinity gradient dominates the near-surface density structure and thus exercises a major control on the system's response to wind.

Those familiar with the inlets of Canada's Pacific Coast are aware of the strong winds that can occur on these long, steep-sided arms of the sea. Sometimes they take the form of diurnal sea breezes, developing in the morning and dying away in the evening (Pickard, 1961), or they may be katabatic in nature, sweeping down with great intensity especially during the winter on certain mainland inlets. Superimposed on these shorter period events are frequent winds of one to a few days duration associated with the passage of weather patterns moving in from the Pacific Ocean. The impact of these wind events is considerable: observations in this study show that the surface layer thickness can change by a factor of 2 or more in a few hours.

Alberni Inlet is one of the more extensively studied estuaries on Canada's Pacific Coast. Tully (1949) took a series of observations in which the nature of the circulation was described with a view to predicting the effects of pollution from a pulp mill. Since Tully's study intermittent observations have continued. Pickard (1963) reviewed some of these data with special reference to the exchange of deep water. Severe damage at Port Alberni resulting from the tsunami of March 1964 prompted Murty and Boilard (1969) to develop a barotropic model of the inlet using numerical techniques.

It has been known for a long time that wind influences the surface structure of inlets. Sandstrom (1904) found that the distribution of low-salinity water in the Gullmarfjord depended upon wind direction. Pettersson (1920) studied the same phenomenon using regression analysis on a long series of daily salinity measurements taken at Borno.

In his analysis of Alberni Inlet, Tully briefly described some of the wind effects. He found that up-inlet winds tend to increase the depth of the upper zone and he included a diagram to show that the surface layer increases in thickness from 3 to about 7 m following three days of strong up-inlet winds. He also attempted to relate the wind effect to other factors such as river discharge, but these results were not conclusive.

In an intensive set of current measurements taken from an anchored ship in Knight Inlet, Pickard and Rodgers (1959) found some evidence of deep (40–100 m) compensating currents associated with wind stress in addition to surface effects. They also found that up-inlet winds could reverse the surface flow only for a limited time, suggesting the buildup of pressure gradients to oppose the wind action.

Gade (1963) and Johannessen (1968) described certain wind effects measured in the Oslofjord area of Norway. Both observers found surprisingly long phase lags (of about 10 h) between the wind and the near-surface current. Gade (1970) discusses cur-

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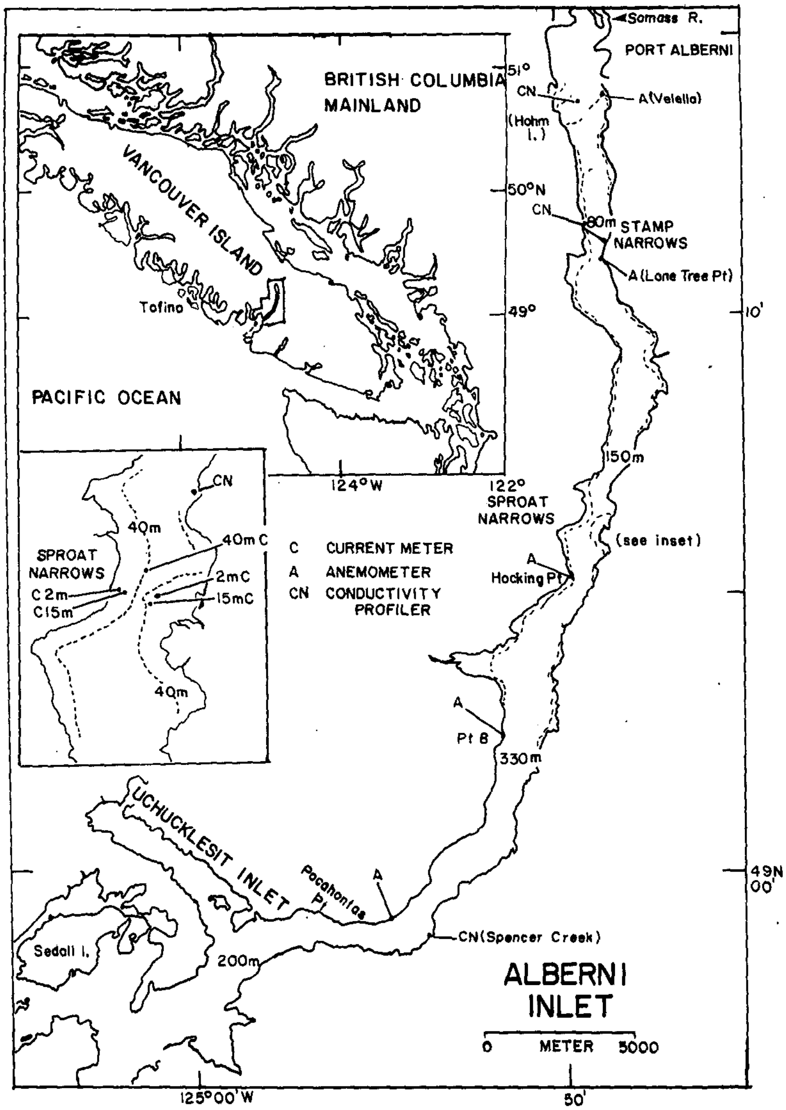

FIG. 1. Map of Alberni Inlet showing location of instruments. Alberni Inlet is located on the Pacific side of Vancouver Island (see upper left insert).

rent measurements in the Vestfjord taken after a few hours of fresh up-inlet winds which indicate a three-layer current system with inflow at the surface and at depth and with an outflow between. He also demonstrated that persistent winds set up strong horizontal salinity gradients along the axis of the fjord.

Most of these studies have concentrated on the steady-state effects produced by the wind; yet it appears likely that in fjords the stratified waters are in a state of almost continuous fluctuation as the surface is subjected to a rapidly changing wind stress. The purpose of this study is to explore the time-dependent structure of this response and to demonstrate its behavior under the influence of a changing wind field.

2. Instrumentation

In order to understand the effects of wind on the surface waters of Alberni Inlet, measurements of the following parameters were taken from February to May, 1971: currents, conductivity structure, wind speed and direction and river runoff.

Four Lambrecht anemometers recorded wind speed and direction at representative points along the inlet. Prior to the installation of these instruments, data were available from an anemometer mounted on the roof of a barge located at the head of the inlet (Fig. 1).

The instruments were mounted on 2 m poles grouted into the rock in positions as exposed as possible. The intention was to obtain data that would be representative of wind stress over the water. *Obviously,*

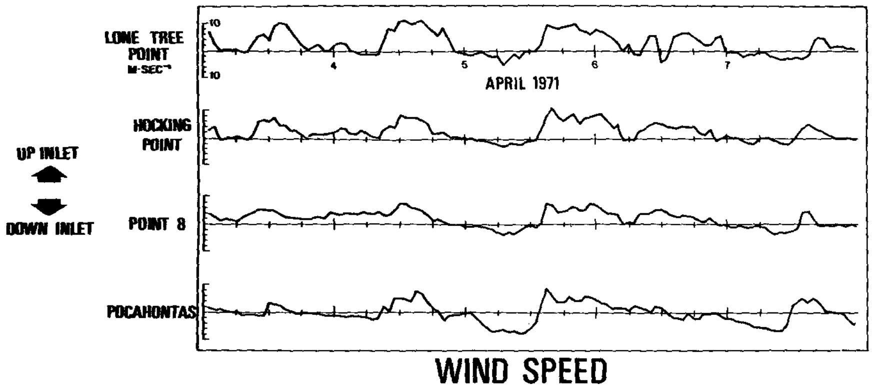

FIG. 2. Sample record of wind measurements at four locations.

this was possible only in the loosest sense, since the rock itself must influence the measured wind speed; nevertheless, field experience did indicate that the locations were reasonably representative of wind conditions over the water.

Current measurements were obtained at various points along the inlet (Fig. 1) by the Canadian Hydrographic Service both for tidal analysis as well as support of the present study. Only the current records from Sproat Narrows were appropriate for this experiment. These meters were located at 2 and 15 m. The necessity of avoiding the shipping route and the danger of anchoring buoys too near the submarine cables influenced the choice of mooring locations. Neyrpic current meters were used; these instruments record integrated 10 min currents on punched paper tape. The Hydrographic Service also took drift-pole and drogue measurements.

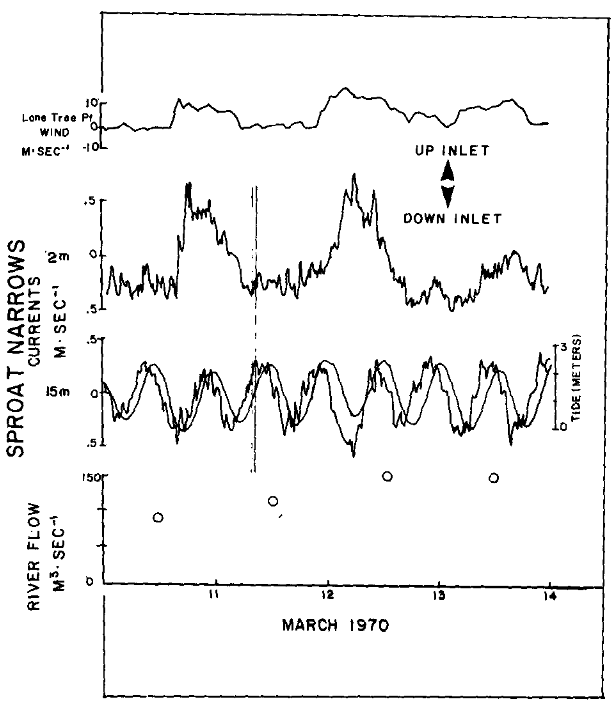

FIG. 3. Wind, current and mean daily river discharge. Measured tidal elevation at Port Alberni (smooth curve) is superimposed on 15 m current. The vertical double line indicates time of drift-pole measurements shown in Fig. 4.

Vertical profiles of electrical conductivity over the upper 9 m were measured every 15 min using instruments described by Farmer and Osborn (1972). There were three instruments; one was moored to a floating dock adjoining Holm Island and the remaining two were attached to log booms located near the south shore just up-inlet of Stamp and Sproat Narrows (Fig. 1). During the last month of the experiment the Stamp Narrows instrument was moved to Spencer Creek. In addition, measurements were taken for a week with an instrument moored on each side of Sproat Narrows to search for transverse isohaline slopes.

In waters that have a high-salinity stratification electrical conductivity profiles can be used to provide an estimate of density structure, especially during autumn, late winter and spring when the water column may be almost thermally homogeneous.

River discharge was obtained from a gage on the Somass River at the inlet head. Although long-term tidal measurements are taken at Port Alberni, the Hydrographic Service greatly extended the collection of tidal data during this program with the installation of seven supplementary gages along the Inlet.

3. Observations

Fig. 2 shows data taken from the four anemometers. The wind speed is shown as either up-inlet or down-inlet, since at the four locations chosen the transverse component was negligible. A remarkable feature of the winds in Alberni Inlet is that, although they appear to be fairly uniform at any given time over a large part of the channel, the wind is noticeably weaker nearer the mouth. This effect appears to be due to the influence of the local mountains which tend to concentrate the winds between Spencer Creek and the inlet head, while protecting the inlet to the west of this point. This is especially true of up-inlet winds, which occur most frequently. Down-inlet winds

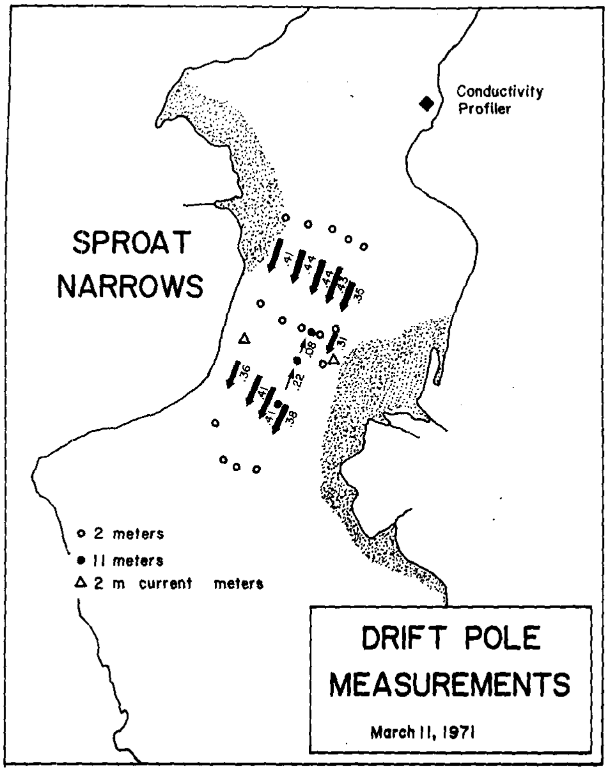

FIG. 4. Drift-pole and drogue measurements (kt) at Sproat Narrows (1 kt = 51.48 cm s^{-1}). The circles represent the measured locations of the drift poles; the arrows represent computed speeds (courtesy Canadian Hydrographic Service).

may be slightly accentuated west of Spencer Creek. These effects are indicated in Fig. 2.

We have only considered the current measurements taken at Sproat Narrows in this analysis. The data are in the form of components resolved along the major axis of the measured distribution of directions and were supplied by the Canadian Hydrographic Service. Histograms showing the distribution of currents with respect to direction from each instrument indicate that there is usually only a small transverse component.

Fig. 3 shows a typical section of Sproat Narrows current data at depths of 2 and 15 m. Only one each of the two 2 and 15 m records are included, both from the north side of the channel, but they are representative of measurements on the south side, which they follow closely. Superimposed on the 15 m current record is a plot based on hourly values of tidal height measured at Port Alberni. The figure also includes wind observations and average daily river discharge figures for the Somass River.

The 2 m current data show a net down-inlet flow; there is also a tidal component, though this is much less apparent than in the 15 m record. The most striking feature of the data, however, is the strong up-inlet flow which appears to be strongly correlated with the wind. There is also a fair amount of high-frequency energy in the current.

At 15 m the current is closely related to the tidal height which it precedes by about 2 h, but there does not appear to be any obvious or consistent relationship with the wind.

The Canadian Hydrographic Service also undertook a number of drift-pole measurements in the Sproat Narrows area. The purpose of these was to gain some insight as to the extent to which the 2 m current records were representative of the general surface flow. In addition, some 11 and 20 m drogue measurements were taken. Fig. 4 shows a typical set of drift-pole data collected on 11 March. A vertical double line in Fig. 3 indicates the timing of the measurements. The records show that the current is approximately 10–20% greater in the middle of the inlet than at the sides. The upstream flow indicated by the 11 m drogue seems consistent with the 15 m current measurements shown in Fig. 3.

The conductivity records showed that the density structure was almost continually changing. Fig. 5 shows contours of constant conductivity on a plot of depth against time and indicates the rapid deepening of the pycnocline that can occur with strong up-inlet winds.

Table 1 shows the times and locations of instrument deployment. There were inevitably some instrument failures and the data presented in this paper have been selected accordingly.

4. Parameterization

Contour plots of the type shown in Fig. 5 provide a very detailed description of the conductivity distribution, but for analyzing large quantities of data it is more convenient to summarize the results at any given time with appropriate parameters. Two parameters seem relevant: a length scale associated with the thickness of the surface layer and a parameter indicating the extent of the mixing.

The thickness length scale H_f is defined as that thickness of fresh water which would occur if the measured water column were separated into two layers: a surface layer of fresh water and a lower one whose salinity was equal to that found at the greatest depth of measurement H. The lower layer of thickness $H-H_f=H_s$ is understood to include all the salt in the original water column. Thus,

$$\text{fresh-water thickness}=H_f=\left[H-\frac{1}{S(H)}\int_0^H S(z)dz\right],$$

where H is the greatest depth of measurement and $S(z)$ the salinity at depth z.

The second parameter ΔPE represents the difference between the potential energy per unit cross section of the two layer system just defined, and the potential

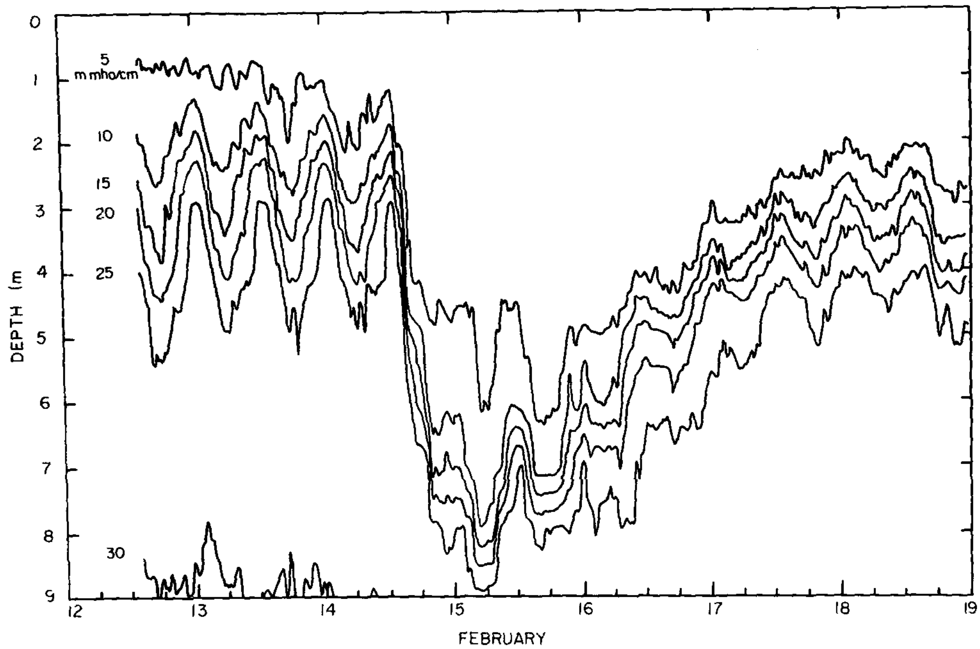

FIG. 5. Contours of constant conductivity taken at Hohm Island. Wind and 2 m current measurements for these data are shown in Fig. 8 (from Farmer and Osborn, 1972).

energy per unit cross section of the observed distribution. The potential energy is calculated with respect to the lowest probe. Let the origin be at the depth of the lowest probe and the positive z axis point vertically upward; then the potential energy difference is

$$\Delta PE = g\int_0^H z\rho_m(z)dz - \tfrac{1}{2}g[\rho_s H_s^2 + \rho_f(H^2 - H_s^2)],$$

where ρ_m is the measured density distribution and ρ_s and ρ_f are the densities of the salt-water and fresh-water layers, respectively.

Determination of salinity and density requires a knowledge of temperature. As mentioned earlier, only conductivity was monitored since the salinity gradient was such that it dominated both conductivity and density profiles. It is possible to estimate both H_f and ΔPE by using salinity and density profiles calculated on the basis of a constant temperature distribution. Some temperature data are available, however, and have been incorporated in the following way.

The data are in the form of weekly observations of temperature, conductivity and salinity taken with an *in situ* salinometer alongside each instrument and also river water temperature taken every few days at the river discharge gage on the Somass River. Interpolating between the measurements two basic temperatures were estimated: that of unmixed river water entering the inlet and that of sea water at 9 m.

TABLE 1. Dates and locations of instruments.

Instrument	Location	Depth of Mooring (m)	Date In	Date Out
Conductivity profiler 1	Hohm Island	16	12 Feb	12 May
Conductivity profiler 1	Sproat Narrows North	20	12 May	20 May
Conductivity profiler 2	Stamp Narrows	20	12 Feb	7 Apr
Conductivity profiler 2	Spencer Creek	36	7 Apr	11 May
Conductivity profiler 3	Sproat Narrows South	29	8 Feb	20 May
Current meters* (2 m)	Sproat Narrows		9 Feb	10 May
Anemometer 1	Pocahontas Point		24 Feb	11 May
Anemometer 2	Point 8		24 Feb	11 May
Anemometer 3	Hocking Point		24 Feb	20 May
Anemometer 4	Lone Tree Point		25 Feb	20 May

* Instruments installed and maintained by Canadian Hydrographic Service.

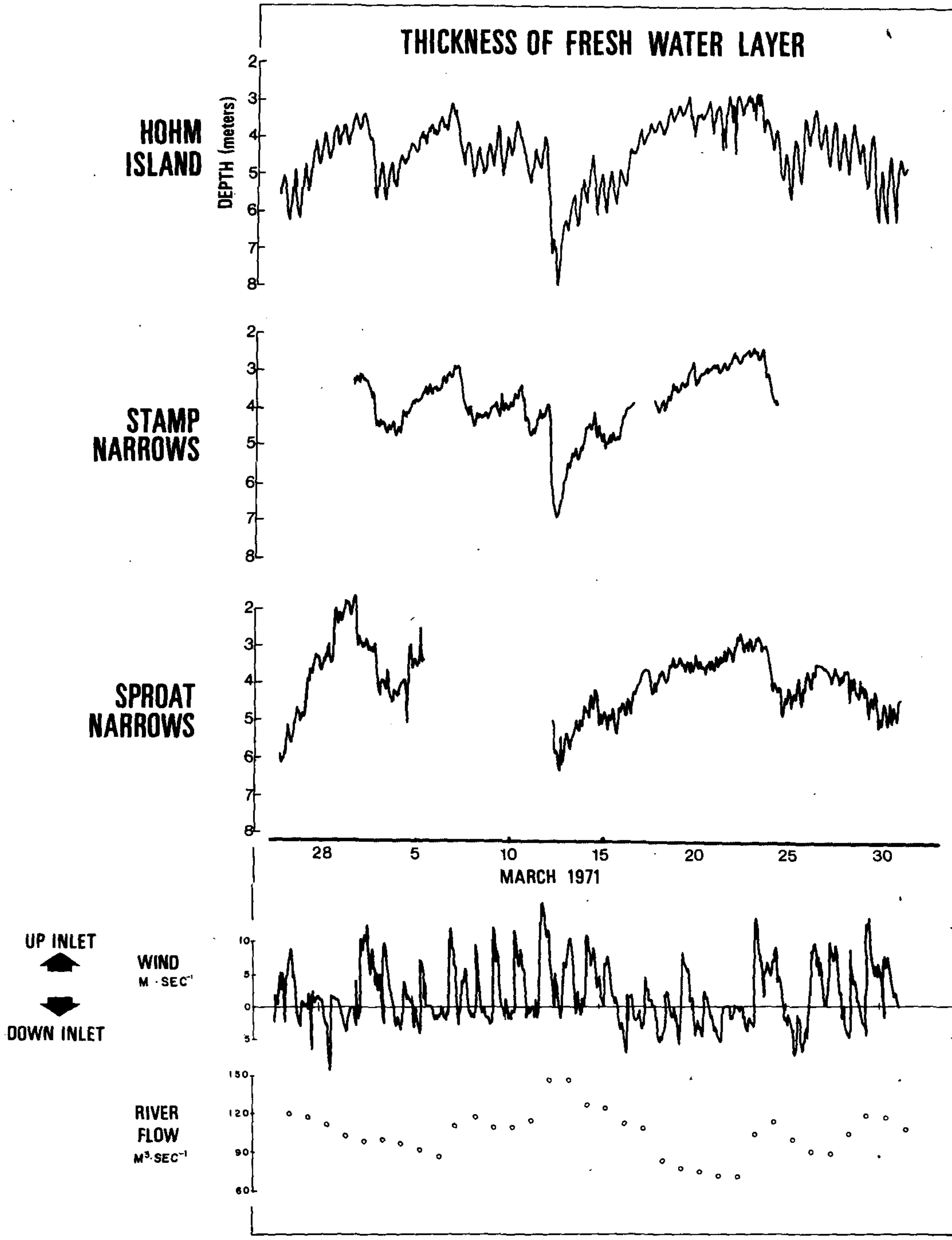

FIG. 6. Thickness of fresh-water layer (33 days).

The temperature of the water at 9 m rarely changed more than 0.1°C in one week. River water temperatures varied 3° or 4°C in one week in extreme conditions. Temperatures at depths less than 9 m were calculated on the assumption that the measured conductivity indicated the extent of mixing between river water and the water at 9 m, and that temperature differences were linearly related to the conductivity differences. This is a very rough approximation, but probably as good as any other under the circumstances. The worst possible error in σ_t estimates due to lack of temperature data would be less than 10%; typically the error would be much less than 5%.

It is worth noting that the effect of temperature on the conductivity of sea water increases with increasing salinity, yet in the case considered here *the*

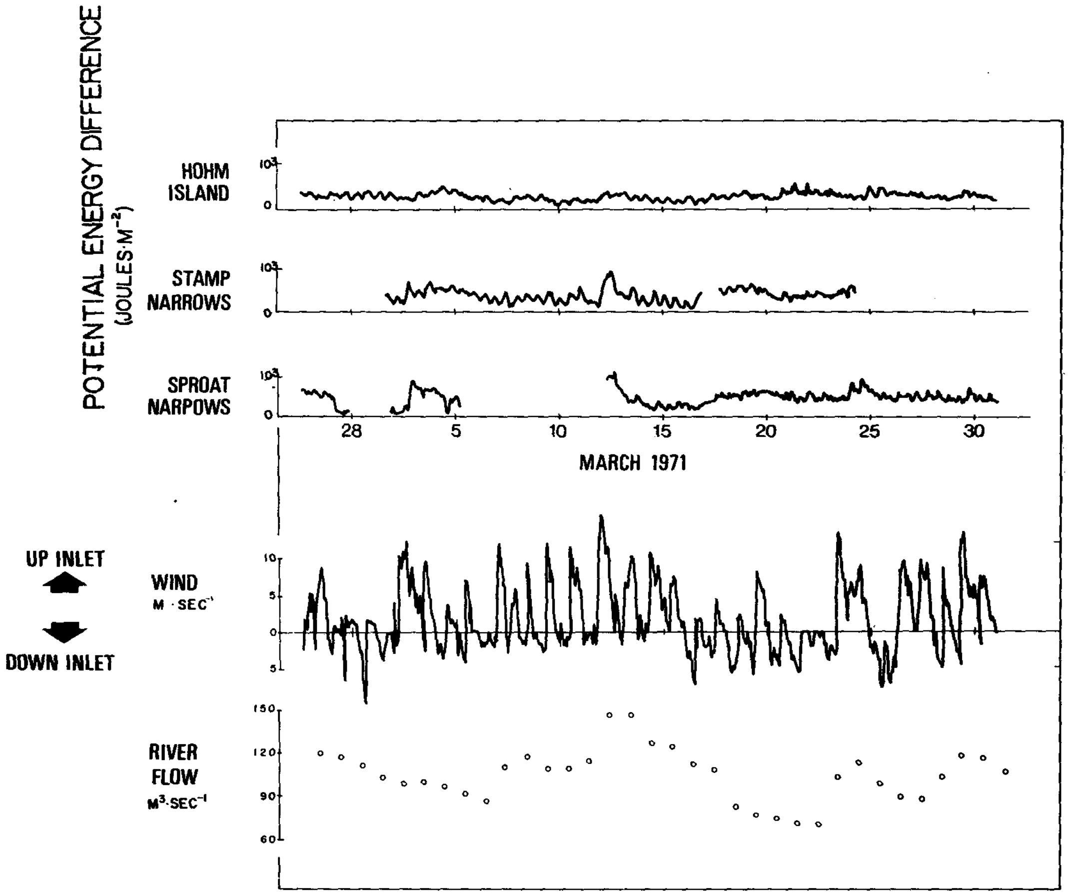

FIG. 7. Potential energy difference, Lone Tree Point wind and Somass River discharge (33 days).

depth of highest salinity and hence the depth most sensitive to temperature errors was also the most thermally stable. This condition tends to favor the type of approximation made above. On the other hand, heat exchange through the surface of the inlet is completely neglected.

The choice of parameterization is necessarily rather arbitrary. In addition, the two estimates of H_f and ΔPE are unlikely to be independent of each other. For example, when the surface layer becomes very thick, the conductivity gradient associated with the halocline may influence the conductivity at depth H. An extreme situation of this sort occurred on 15 February (Fig. 5). This change in turn will alter the salinity estimate for the salt-water layer and thus the ΔPE estimate as well. The weekly average of salinity estimates was used in computing the density of the lower layer in an attempt to reduce this effect. The problem stems from the fact that 9 m was not always an adequate depth for monitoring the type of effects with which we are concerned. Nevertheless, the two parameters do seem to reproduce the main features indicated by the contour plots.

An advantageous consequence of the vertical integration involved in the parameterization is that it tends to average out the effect of relative inaccuracies between the probes in any one probe chain. The parameter estimates were based on successive observations taken 15 min apart. Since the data were to be compared with hourly wind values, hourly averages of each parameter estimate were taken. Straight lines have been drawn between these hourly values in the plots presented in this paper.

5. Discussion

Figs. 6 and 7 show fresh-water thickness and potential energy difference data taken from the three main stations over a period of 33 days. The Hohm Island record represents the longest unbroken stretch of data obtained.

The fresh-water thickness appears to undergo a series of sudden increases associated with strong up-inlet winds, followed by a gradual return to equilibrium. The rapid fluctuations, especially at Hohm Island, are dominantly semidiurnal. However, there is little obvious relationship between the diurnal wind component and the fresh-water thickness. The potential energy difference variations also seem to be associated

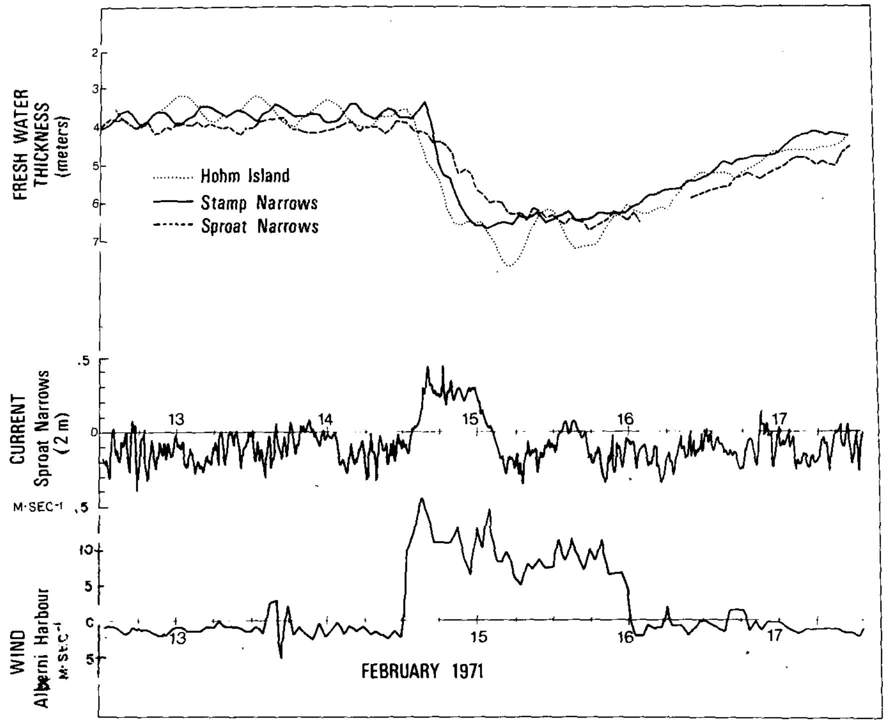

FIG. 8. Fresh-water thickness, 2 m current and wind (5 days).

with the wind; the effect is usually greater at Stamp and Sproat Narrows than at Hohm Island.

It is not surprising that increases in the river discharge associated with heavy precipitation frequently occur at about the same time as extra strong winds. Significantly, however, even in the absence of these fluctuations, changes in H_f and ΔPE occur with strong winds.

For example, Fig. 6 shows that on 2 March an increase in fresh-water thickness of 2.5 m occurred; there was a strong up-inlet wind on that occasion but there was no large change in river discharge. Similarly, Fig. 7 shows a noticeable increase in mixing energy on that date, especially at Stamp and Sproat Narrows. It seems likely that most of the observed changes are a consequence of wind stress.

To observe these processes in greater detail we consider the situation described by Figs. 8 and 9. The following sequence of events occurred. After a period of comparative calm, a strong up-inlet wind arose on 14 February. Within 3 h the current records at 2 m in Sproat Narrows responded with an up-inlet current of about 0.5 m s^{-1}. The fresh-water thickness increased suddenly, first at Hohm Island, then at Stamp Narrows and somewhat later at Sproat Narrows.

Fluctuations in thickness at Hohm Island on 15 February, which may have been associated with wind-stress changes at that time, do not markedly appear at Stamp Narrows and not at all at Sproat Narrows. Moving down-inlet from the Hohm Island to the Sproat Narrows station, we see these fluctuations become progressively gentler. Moreover, the greatest change of thickness between the 14th and 15th of February occurs at Hohm Island, but all three stations show similar changes during the slow return to equilibrium.

Fig. 8 demonstrates another important feature common to most of the conductivity data. The internal semidiurnal oscillation shows up most strongly at Hohm Island. It is still evident at Stamp Narrows, but only with about one-half the Hohm Island amplitude. At Sproat Narrows it occasionally shows up, but at this station these fluctuations are mainly lost in the background noise.

During a pilot study in August 1970, temperature measurements taken at the float plane dock on the eastern edge of Port Alberni harbor, across from Hohm Island, indicated essentially the same results: an internal semidiurnal oscillation of surface thickness in phase with the surface tide. Tully (1949) also observed an internal oscillation in the harbor. It seems likely that this is an internal tide generated over the gently sloping bottom contours at the northern end of the harbor. Rattray (1959) has shown how similar topographies can cause internal tides on an open coast. Outside of the generating zone the disturbance can be expected to have the properties of a progressive internal gravity wave. The lower amplitude observed at Stamp Narrows presumably indicates the presence of frictional damping.

Turning now to Fig. 9, we see that there is a strong increase in ΔPE when the wind picks up. Fig. 9 also

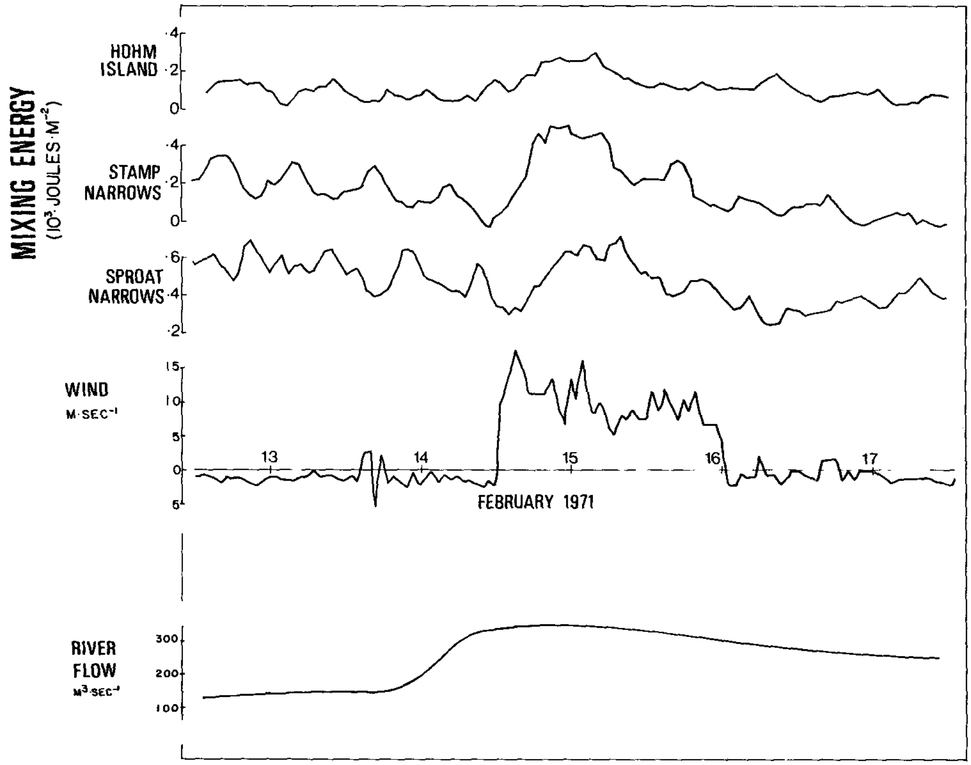

FIG. 9. Potential energy difference, wind speed and Somass River discharge (5 days). The discharge curve is taken directly from the trace produced by the recording river flow gage.

shows the river flow which is taken directly from the curve traced on the original discharge record. It is interesting to note that the flow increases and reaches its peak before the wind starts, but no large change in H_f or ΔPE occurs at this time. These results tend to support the hypothesis that most of the changes in these two parameters depend upon wind rather than discharge. On the other hand, there does appear to be a slight decrease in ΔPE at Stamp and Sproat during the first 12 h of 14 February before the wind begins.

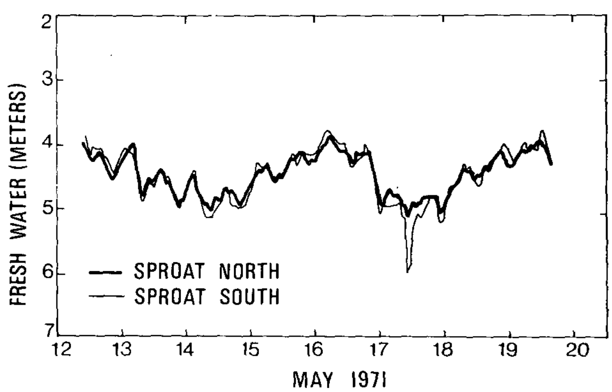

FIG. 10. Comparison of fresh-water thickness on north and south sides of Sproat Narrows.

The potential energy difference also shows a marked variation of semi-diurnal frequency. Tully (1949) observed a similar effect.

On 12 May the conductivity profiler at Hohm Island was moved down to the north side of Sproat Narrows (Fig. 1). The purpose of this change was to search for transverse gradients in the density profile, such as might result from inertial or rotation effects. Fig. 10 shows the corresponding fresh-water thickness records; apart from a curious discrepancy on 17 May for which there is no obvious explanation, measurable transverse gradients did not occur.

Between 7 April and 11 May the Stamp Narrows conductivity profiler was stationed at Spencer Creek (Fig. 1). This move was made to observe wind effects in the lower part of the inlet. The records from this station are not good; the salinity gradient is rather less than in the upper reaches of the inlet and the noise level is much higher. During this period of observation, winds of up to 14 m s^{-1} were recorded, but it is clear from the data, which are not presented here, that major variations in the fresh-water thickness are not present. On the other hand, the data show quite large changes in the potential energy difference associated with strong winds.

6. Summary

These observations have provided some insight into the way in which a stratified inlet responds to wind stress. Strong up-inlet winds produce a rapid thickening at the inlet head. This distortion appears to propagate back down the inlet suffering an attenuation as it travels. The return to equilibrium can take several days; the inlet's response is similar to that of a heavily damped mechanical system.

Using a simple parameterization of the data, it is possible to see how wind affects the intensity of the stratification. As might be expected, mixing increases with strong winds, but the effect is more noticeable away from the inlet head.

Current measurements taken by the Canadian Hydrographic Service at Sproat Narrows have shown that the movement of water at a depth of 2 m is closely coupled to the wind; at 15 m the current is mainly tidal.

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