Wind Effects on Currents Observed in Juan de Fuca Submarine Canyon[1,2]

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ABSTRACT

Juan de Fuca submarine canyon has depths exceeding 200 m extending completely across the continental shelf. Observations of currents in the canyon during winter 1970 showed relatively large currents and large excursions both in- and out-canyon. Three major flow reversals appear related to major wind reversals as a compensating current to an Ekman surface regime. A fourth wind reversal, not accompanied by flow reversal, indicates that along-canyon density gradients are also important.

1. Current measurements

Juan de Fuca submarine canyon is unique in that the head of the canyon intersects what is thought to be a glacial trough (Carson and McManus, 1969); consequently, depths exceeding 100 fathoms (183 m), the approximate offshore boundary of the continental shelf, extend completely across the shelf into the Strait of Juan de Fuca (Fig. 1). This intersection forms a sill-like feature of about 230 m depth near the outer edge of the shelf, and several depressions exceeding 300 m exist between the sill and the Strait.

An exploratory subsurface current-meter mooring was deployed on the sill (228 m) in January 1970. Braincon current meters (rotor and vane, model 381) were used to sample continuously 10-min averages of speed and histograms of direction at four depths. Buoyancy was provided by 0.91 m diameter steel spheres (surplus submarine net floats) at the top and middle of the mooring. The lower half of the mooring only was retrieved in February by acoustical release (ORE) of the anchor (two railroad wheels). Shoaler meters and a pressure recorder were lost when the upper half of the mooring apparently broke loose during a storm. Useful records were obtained for 22 and 12 days at 175 and 225 m, respectively. The precision of the current measurements was about 0.3 cm sec^{-1}. Winds were measured six times daily at Umatilla Light Ship 40 km from the mooring (Fig. 1).

The records showed unidirectional flow out-canyon at 175 and 225 m (53 and 3 m above the bottom) for most of the common 12 days. The flow then reversed at both meters, and it was primarily unidirectional in-canyon at 175 m for the following 10 days. Tidal oscillations were observed in the records, but with few exceptions the amplitudes were smaller than the mean flow. Progressive vector diagrams (Fig. 2) show these features as well as two additional reversals of shorter duration at 175 m. The largest excursions were about 240 and 160 km out- and in-canyon, respectively, which were exceedingly large when compared to the approximate 80-km distance following the canyon-trough from the sill to the mouth of the Strait.

The records were subdivided corresponding to the two major excursions into series of 24 semidiurnal cycles at both depths followed by a series of 18 semi-

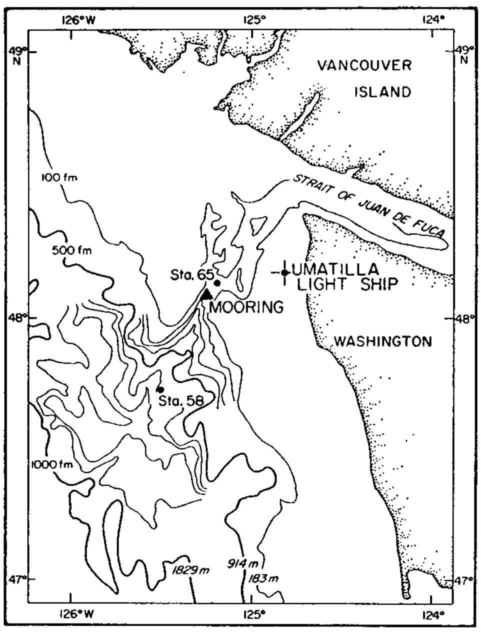

FIG. 1. Chart of Juan de Fuca submarine canyon and vicinity. Two closed contours within the canyon are shoal areas. Hydrographic stations 58 and 65 were occupied by ***Brown Bear*** at 0800 GMT 26 January and 0500 GMT 27 January, 1961, in 948 and 248 m of water, respectively.

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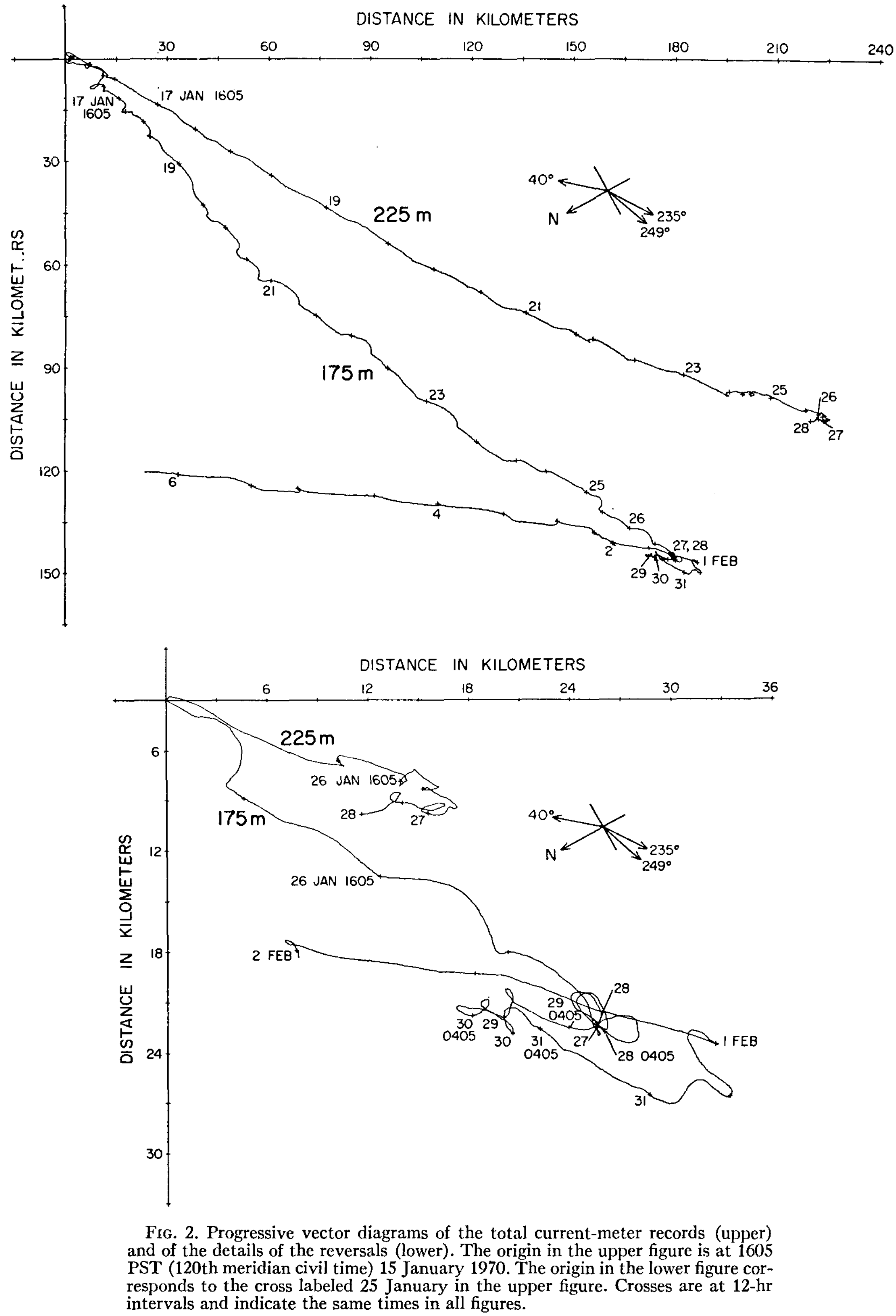

FIG. 2. Progressive vector diagrams of the total current-meter records (upper) and of the details of the reversals (lower). The origin in the upper figure is at 1605 PST (120th meridian civil time) 15 January 1970. The origin in the lower figure corresponds to the cross labeled 25 January in the upper figure. Crosses are at 12-hr intervals and indicate the same times in all figures.

diurnal cycles at 175 m. Some characteristics of these records are given in Table 1. Mean currents were calculated, and a fast Fourier transform algorithm was used to estimate harmonics (Cannon, 1971) along the axes of the vector mean currents. The M_2 components in the 24-cycle series were in phase at the two

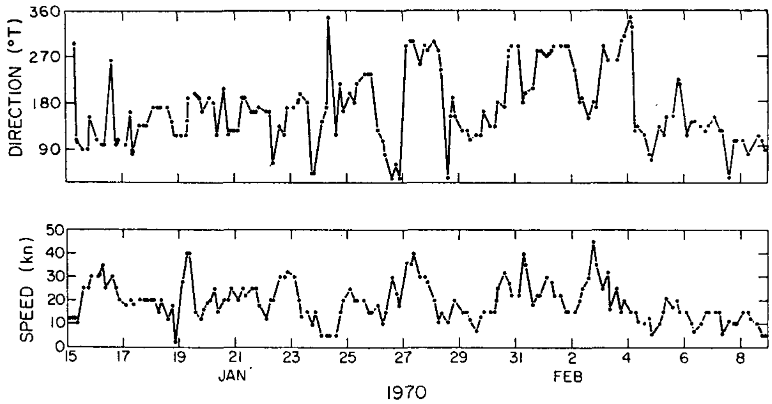

FIG. 3. Wind speed (lower) and direction (upper) measured at Umatilla Light Ship. Observations at 0300, 0700, 0900, 1500, 1900 and 2100 PST (120th meridian civil time) daily. The time origin is 0000 PST 15 January 1970.

depths within the precision of the measurements. Maximum M_2 component out-canyon occurred when the predicted tide was falling from high to low on the adjacent coast and about 2–3 hr prior to maximum predicted ebb at the mouth of the Strait. The difference in the variances (kinetic energy of the fluctuations) at the two depths primarily occurred at periods >50 hr. The initial reversal also was observed at 225 m, and it is possible that the in-canyon currents were of comparable magnitude to those at 175 m.

2. Relation of current reversals to observed winds

A major low-pressure system was stationary in the Gulf of Alaska during 16–26 January producing southerly winds of about 20 kt (1 kt = 0.514 m sec^{-1}) along the Washington coast (Fig. 3). This system moved inland on the 27th, and high pressure accompanied by strong northwesterly winds formed along the coast. A second low-pressure system dominated during 29–30 January, moved inland on the 30th, and was followed by a second high-pressure system with strong northwesterlies. The latter system persisted until it moved inland on 4 February and weak low pressure then formed offshore producing weak southerly winds of about 5–15 kt.

The three major flow reversals observed in the canyon (Fig. 2) appear related to major wind reversals (Fig. 3) as a compensating current to a surface Ekman regime (Ekman, 1905). Winds along the coast in the winter are predominately southerly which would produce an onshore component in the surface drift. A compensating offshore component at the bottom would correspond to out-canyon flow, which is what was observed. A similar situation has been observed farther south on the continental shelf of Washington (Hopkins, 1971), and observations of surface currents and winds at Umatilla Light Ship also support the existence of an Ekman regime at the surface (Marmer, 1926). In the present case the offshore component of the barotropic pressure gradient due to the sea-surface slope is transmitted to waters in the canyon, the lower layer of the two-layer system (Fig. 4), and along-shore

TABLE 1. Characteristics of the series of 24 and 18 semidiurnal cycles.

Depth (m)	Amount time speeds exceeded: 25 cm sec^{-1} (%)	Amount time speeds exceeded: 50 cm sec^{-1} (%)	Vector mean current: Speed (cm sec^{-1})	Vector mean current: Direction (deg)	M_2 component: Amplitude (cm sec^{-1})	M_2 component: Variance (cm^2 sec^{-2})
24-cycle series						
175	45	3	22	249	10	234
225	47	10	23	235	13	479
18-cycle series						
175	40	17	17	40	—	—

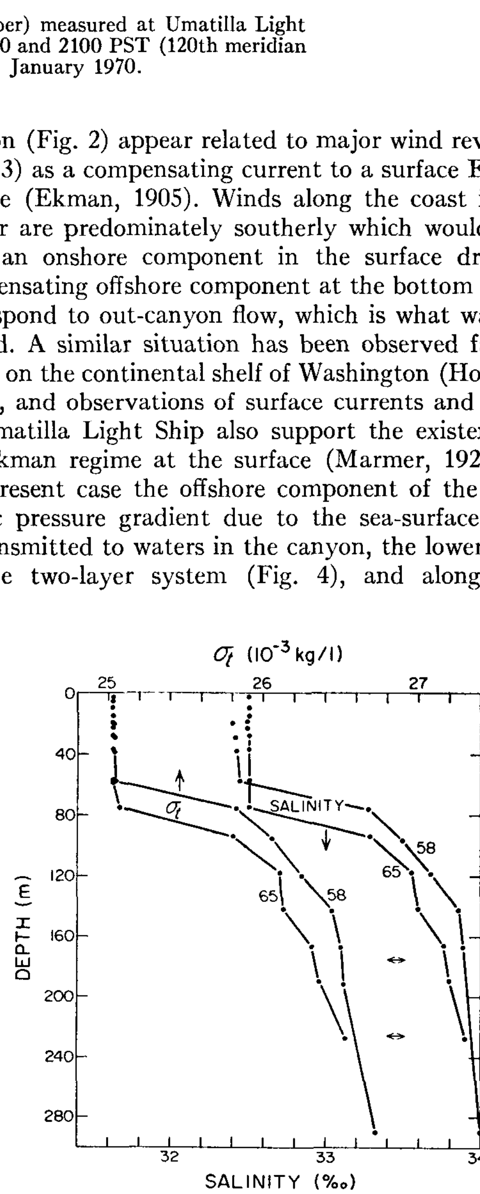

FIG. 4. Salinity and σ_t profiles for the 1961 *Brown Bear* stations shown in Fig. 1. Horizontal doubled-headed arrows indicate depths of current meters in 1970 experiment.

components are suppressed below the level of the surrounding continental shelf. Ekman (1906) showed this transmission to be more effective in a two-layer ocean with uniform density in the upper layer, the approximate winter conditions, than with density linearly changing with depth in the upper layer. The flow reversals observed at 175 m on 28–29 January, 30 January, and 1 February (Fig. 2) follow wind reversals by 1–2 days, which is approximately in agreement with Ekman's predictions (the half pendulum day at this latitude is 16.1 hr). The relatively large rotary currents at 175 m on 27–28 January followed a time of relatively weak southerly winds and appeared to be of inertial period. The first reversal was also observed at 225 m and apparently preceded the reversal at 175 m, although it is somewhat difficult to tell because of the differing rotary characteristics. The 14° direction difference in the vector mean currents at the two depths during the first 12 days cannot be explained as a simple bottom Ekman layer. It is likely that the Coriolis effect contributes to rotating the current to the left as the bottom is approached, and it is possible that the flow follows lateral bottom contours, which appear to rotate slightly to the right coming up from the bottom when one looks out-canyon. However, these data are insufficient to describe the boundary layer.

3. An anomalous case

An exception to the above occurred on 4 February when the winds again reversed to southerly with speeds of about 5–15 kt (Fig. 3), but the currents remained in-canyon at least until 7 February, the end of the record. Fig. 4 shows that winter stratification, although from another year, is not strictly represented by a two-layer model, but that horizontal density gradients can exist along the canyon in the lower layer. Thus, in the canyon-trough there can be a baroclinic component to the pressure gradient, a situation not unlike that of an estuary. The baroclinic pressure-gradient forces due to the density differences in Fig. 4 correspond to in-canyon flow. Thus, southerly winds would have to have some minimum magnitude to generate sufficient sea-surface slope for the barotropic component of the pressure gradient to reverse the baroclinic component. If a balance is assumed only between the baroclinic and the barotropic pressure gradients, then the data in Fig. 4 can be used to calculate that in order for southerly winds to reverse the density effect at the sill, a sea-surface slope of about 10^{-6} perpendicular to the coast is required. Because the Coriolis term in the along-canyon equation of motion is zero in the canyon, errors would be expected primarily from the stress gradient term. Observations in 30–40 m deep East Sound estuary (Rattray, 1967) show that near the bottom the stress gradient term is about $0.1–0.3\times10^{-6}$ and of the same sign as the baroclinic component. The same observations were used to calculate a sea-surface slope of 2×10^{-6} with winds of 10–15 kt. Under less bounded conditions of the open coast and with greater depths, winds of this speed would be expected to result in smaller slopes, possibly accounting for the absence of current reversal at the end of the record in Fig. 2.

4. Concluding remarks

The observations described here are different from currents measured in La Jolla and Scripps submarine canyons (Shepard and Marshall, 1969) where fluctuations of much higher frequency were observed. Mean currents described here for the major excursions were comparable to maximum currents observed by Shepard and Marshall, although no storms occurred during their observations. Inman (1970), however, has observed maximum currents of 3.6 kt in Scripps Canyon during storms.

The extent of the currents along the canyon-trough is unknown from the measurements described here, but the long excursions suggest possible interaction with bottom water in the Strait of Juan de Fuca. That interaction occurs is evidenced by 15 of 100 bottom drifters (Moorse *et al.*, 1968) released in the outer canyon-trough in October 1966 being retrieved in the Strait (Moorse, personal communication). The large out-canyon excursion with speeds sufficient to transport sediment suggests a mechanism and a route for transportation of sediment found in Nitinat fan (Carson and McManus, 1969). The source of the sediment either could be from inside the Strait of Juan de Fuca (Carson and McManus) or could be from the Columbia River drainage, transported north along the continental shelf (Gross and Nelson, 1966), and deposited in the canyon-trough. Also, the water transported in this large out-canyon excursion is at about 200 m and might interact in some way with the possible extension of the California Undercurrent (Wooster and Jones, 1970) along the coasts of Washington and Vancouver Island (Ingraham, 1967) and vice versa.

Upwelling along this coast during summer makes possible the filling of the depressions in the glacial trough with relatively dense water. In autumn following the upwelling season, the density gradients would be directed out-canyon. Thus, the onset of winter storms with southerly winds would augment out-canyon flow. This relatively denser water apparently is flushed out of the trough during autumn and early winter, following which the density gradients become in-canyon (Fig. 4). Further conclusions and testing of the ideas presented here require additional observations (carried out in late 1971).

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