Alongshore Coherence on the Pacific Northwest Continental Shelf (January–April, 1975)

BARBARA M. HICKEY

Department of Oceanography, University of Washington, Seattle 98195

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ABSTRACT

During the winter and spring of 1975, current observations were made simultaneously at five locations between Tofino, British Columbia, and Newport, Oregon, a distance of 480 km. Sea level and atmospheric pressure observations were available at three locations alongshore, and wind observations, at four locations. Computed (Bakun) winds were available at 3° intervals. Low-frequency (<0.6 cpd) fluctuations in alongshore current, alongshore wind, and subsurface pressure were significantly coherent over this distance. Forcing by the local wind dominated the response at each location: alongshore current and sea level fluctuations were significantly coherent with the local alongshore wind, and local phase relationships were consistent with phases predicted by the local model of Hickey and Hamilton (1980). The high alongshore coherence observed in the current and subsurface pressure fluctuations is shown to be a result of alongshore coherence in the forcing, i.e., in the wind field, rather than due to the presence of freely propagating shelf waves: 59% of the variance in the alongshore wind field is contained in an empirical orthogonal function whose amplitude is essentially constant alongshore. This eigenfunction is significantly coherent at all frequencies with the first alongshore current eigenfunction which accounted for 67, 89 and 94% of the variance at mid-shelf near 49, 47 and 45°N, respectively. Moreover, although alongshore phase differences were too small to be associated with freely propagating waves, at the frequencies where alongshore coherence of the current and sea level fluctuations was strongest, the alongshore phase differences were consistent with local wind forcing. Alongshore *differences* in fluctuations could be directly related to alongshore structure in the wind field, providing independent evidence for local wind forcing: 33% of the variance in alongshore current at Tofino (but <5% at other locations) was contained in an eigenfunction that changed sign between 49 and 47°N and was significantly coherent with an alongshore wind eigenfunction with a similar structure. Finally, the seasonal means south of Tofino are shown to be roughly consistent with a dynamical balance between vertically integrated alongshore pressure gradient force and the mean alongshore wind stress.

1. Introduction

In the winter and spring of 1975, current, sea level and wind observations were made simultaneously at five locations between Tofino, British Columbia and Newport, Oregon (Fig. 1). The current observations off Tofino (TF) were made by the Institute of Ocean Sciences, Pat Bay (Huyer *et al.*, 1976); those off Destruction Island, Westport (WP), and the Columbia River were made by the University of Washington; and those off Cascade Head (CH) were made by Oregon State University (Gilbert *et al.*, 1976).

It is first shown in this paper that at each location, current and sea level fluctuations are consistent with forcing by local wind stress. Next, a high degree of alongshore coherence in current and sea level fluctuations is demonstrated and it is shown that this coherence is due to coherence in the wind field itself. As independent support for the hypothesis of local wind forcing, alongshore differences in current and sea level fluctuations are related to alongshore differences in energy input by the local wind field, and alongshore phase differences are shown to be consistent with a local response to traveling wind disturbances and inconsistent with a free wave response.

For historical reasons, the majority of papers on Oregon-Washington shelf circulation have been focused on wave dynamics, in particular, on the existence of freely propagating shelf waves (e.g., Cutchin and Smith, 1973; Huyer *et al.*, 1975; Hsueh and Lee, 1978). Unfortunately, the speed of atmospheric disturbances often tends to be on the order of that of free shelf waves in that area (~400 km day^{-1}) so that it is difficult to distinguish between local and non-local forcing. Moreover, decent wind stations are few and far between, so that, in estimating phase speeds for wind stress, one is often dealing with very noisy, spatially incoherent data or no data. Wang and Mooers (1977) claim very poor coherence in their coastal wind stations and proceed to use the phase speed of the atmospheric pressure disturbances to prove that the wind disturbances travel too fast to be directly forcing the currents (summer, 1973). Since coastal mountain ranges may cause the speed of pressure gradient (i.e., wind) fluctuations to differ from that of pressure fluctuations, it is premature to consider even this case entirely closed.

Another deficiency in most of the shelf wave papers is the neglect of alongshore frictional differences.

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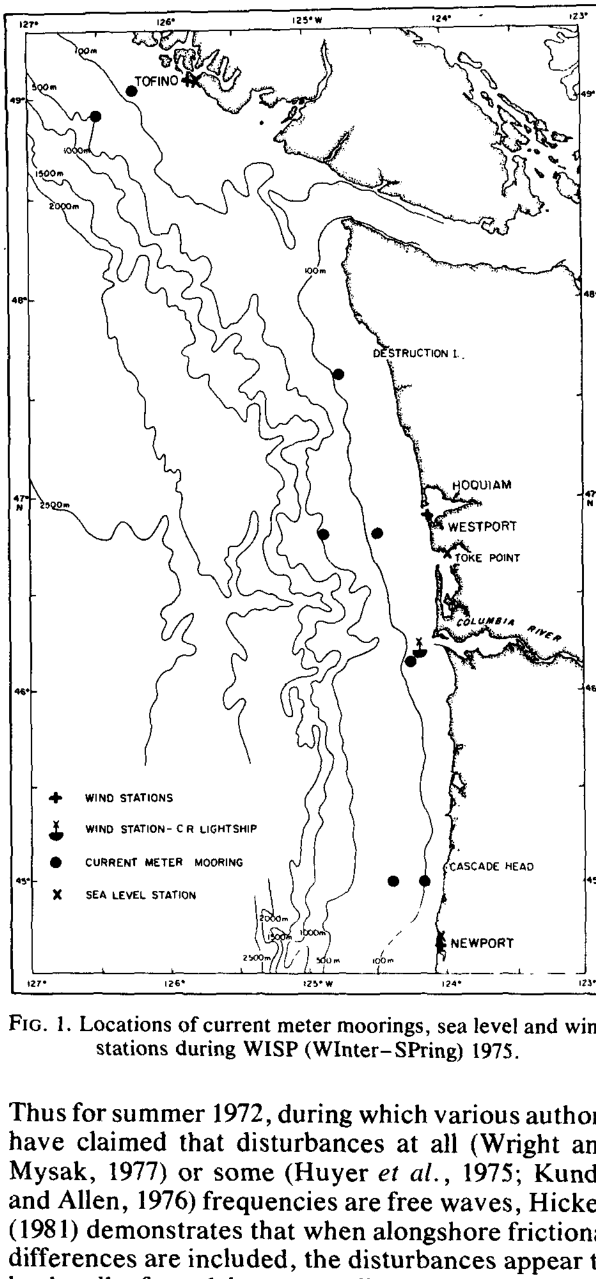

FIG. 1. Locations of current meter moorings, sea level and wind stations during WISP (WInter–SPring) 1975.

Thus for summer 1972, during which various authors have claimed that disturbances at all (Wright and Mysak, 1977) or some (Huyer *et al.*, 1975; Kundu and Allen, 1976) frequencies are free waves, Hickey (1981) demonstrates that when alongshore frictional differences are included, the disturbances appear to be locally forced by a traveling atmospheric disturbance. The most important result of the present study is that also during the first quarter of 1975, local wind forcing rather than free waves is responsible for most of the low-frequency fluctuations in current and sea level. Thus, the significant alongshore coherence observed, as in summer 1972, is caused by large-scale coherence in the local wind field rather than by free, propagating shelf waves.

2. Observations

Current meter moorings consisted of a taut wire with subsurface flotation ~ 15 m below the surface. Record lengths, current meter depths, and sampling intervals are given in Table 1. Aanderaa current meters were used in all cases with the exception of Destruction Island, where a Braincon current meter was used. At Tofino the data were simply decimated to hourly values; at the other locations, the data were filtered to reduce high frequency noise and then decimated to provide hourly values. Short gaps, which occurred due to servicing arrays (see Table 1), were filled by data with spectral characteristics determined from the preceding and subsequent records. At the Columbia River Station, 40 and 20 m data were combined into a continuous record. This is justified by the strongly barotropic character of the observed fluctuations. Previous observations have shown that currents follow the isobaths on the shelf (Smith *et al.*, 1976; Kundu and Allen, 1976), and, therefore, the hourly data were rotated into the local isobath frame of reference (Table 1). In the sections which follow, v and u will indicate along-isobath and cross-isobath components of flow, although they will be referred to as the alongshore and cross-shelf components, respectively.

Hourly values of sea level measured to within ±1 cm were available at Tofino (TF), British Columbia, Toke Point (TP), Washington and Newport (NP), Oregon. Subsurface pressure was obtained by adding atmospheric pressure from Tofino, Hoquiam and Newport, respectively, to the sea level data. Subsurface pressure will be denoted simply "sea level" in subsequent discussions.

Wind speed and direction were measured at Newport, Westport, the Columbia River Lightship, and at Tofino Airport (Fig. 1). The site at Tofino has very poor exposure to coastal winds since the airport is among mountains. Correlations between wind from Tofino Airport and alongshore current (not shown) were essentially zero. Correlations also indicated that wind at Westport was not representative of the wind over the coastal waters. Consequently, only measured winds from Newport (NP) and the Columbia River Lightship (LT) were used in the subsequent analysis. At Newport, the anemometer is located on the south jetty and wind speed and direction are recorded continuously. Time series of hourly data were produced. On the Columbia River Lightship, wind speed and direction are estimated every three hours by Coast Guard personnel. These data were interpolated to hourly intervals.

Six-hourly computations of the wind field on a 3° grid over the northeast Pacific were also available. These estimates of the wind field are generated from 6 h synoptic pressure charts by A. Bakun of the National Marine Fisheries Service. The pressure data are smoothed and interpolated to a three degree grid using forecasting techniques to reject spurious data (Bakun, 1975). Bakun provided coastal wind data at 45°N (B^{45}) and 49°N. Comparison of the

TABLE 1. Location, bottom depth, current meter depths, deployment interval, sampling interval (Δt) and the direction of the local isobath (measured clockwise relative to true north), for current meter moorings.

NAME	LATITUDE, LONGITUDE	DEPLOYMENT INTERVAL	CURRENT METER DEPTHS (m)	DIRECTION OF LOCAL ISOBATH	Δt (min.)	BOTTOM DEPTH (m)
TOFINO	49°02.1N 126°14.4W	28/11/74 - 10/2/75	20,45	-37°	30	100
	49°02.0N 126°14.4W	11/2/75 - 8/4/75	29,53,91	-37°	30	100
TOFINO	48°53.8N 126°29.7W	28/11/74 - 11/2/75	20	-22°	30	200
	48°55.5N 126°32.0W	12/2/75 - 8/4/75	22	-22°	30	200
DESTRUCTION ISLAND	47°35.4N 124°46.3W	23/2/75 - 22/3/75	20	-18°	20	91
WESTPORT	46°49.0N 124°27.2W	11/1/75 - 22/2/75	17,47,72,82	-20°	10	88
	46°48.4N 124°31.1W	22/2/75 - 26/3/75	26,46,66,91	-20°	10	97
WESTPORT	46°48.7N 124°52.2W	23/2/75 - 15/4/75	20,50	-29°	10	184
COLUMBIA RIVER	46°09.2N 124°15.1W	24/2/75 - 27/3/75	40,60,85	-12°	10	91
	46°09.4N 124°15.2W	27/3/75 - 6/5/75	20,60,85	-12°	10	91
CASCADE HEAD	45°00.2N 124°09.4W	27/1/75 - 27/4/75	26,52,76,92	10°	20	100
CASCADE HEAD	45°00.2N 124°23.0W	28/1/75 - 26/4/75	31,55,106,156,206	20	20	225

spectra of Bakun wind at 45°N and wind measured at Newport (44°40′N) indicated significant differences in their alongshore components (see Fig. 11). Differences could be due both to the existence of local structure in the wind field and to inherent limitations in the Bakun wind field.

Since the coastal orientation near Newport and the Columbia River Lightship is very nearly north-south, wind components were not rotated at those locations. Off Tofino, however, the coastal orientation is significantly different from north-south and Bakun's wind was rotated by 37° to obtain alongshore and cross-shelf components (B^{49}_{37}).

Coherence between alongshore components of wind and wind stress (not shown) is high and the phase difference between them is not significantly different from zero at the 95% level. Computing wind stress from wind data amplifies the noise as well as the signal, and correlation coefficients with currents (not shown) are significantly higher for wind than for wind stress. To retain as much of the original coherence and phase information as possible, we have chosen to use wind instead of wind stress in the ensuing analysis, except in the model computations of Sections 3 and 4.

A symmetrical cosine filter spanning 121 h was applied to the hourly current, sea level and wind data to suppress tidal and inertial frequencies. The filter has a half-power point of about 40 h, so that 2.5 days are lost on each end of a time series. The resulting time series were decimated to a 6 h data interval. No filter was applied to the 6 h Bakun winds.

Vector plots of the 6 h mid-shelf (~100 m) near-surface (~20 m) and near-bottom (~90 m) current records and of Newport wind and sea level are shown in Fig. 2. Basic statistics of the 6 h current records are given in Table 2. Time series of the alongshore component of mid-shelf current and of the 6 h wind vectors and sea level are shown in Figs. 3 and 4, respectively. Basic statistics of the wind and sea level records are given in Table 3. Sea level data are given relative to the long-term mean at each location.

3. The mean flow

Representative σ_t profiles in the vicinity of all moorings except Tofino are given in Fig. 5. The near-surface Westport current meter often lies beneath the sharp pycnocline formed by the Columbia River plume and hence might not be expected to demonstrate the behavior of a surface Ekman layer. The other near-surface meters sometimes lie in a relatively well-mixed and thick surface layer and sometimes lie beneath or in a relatively weak pycnocline and would be expected to demonstrate surface Ekman dynamics during most periods. Available data in the vicinity of the Tofino mooring (28 November and 12 February) suggest that the near-surface meter lies in a relatively well-mixed layer (Huyer *et al.*, 1976). Each near-bottom meter is within 10 m of the bottom.

The mean alongshore flow is quasi-barotropic and is generally poleward as is the mean wind stress (Tables 2 and 3). With one exception (Westport, T2), near-bottom directions are consistent with equilibrium Ekman layer dynamics. Results for the surface Ekman layer are less consistent, particularly at the moorings nearest the Columbia

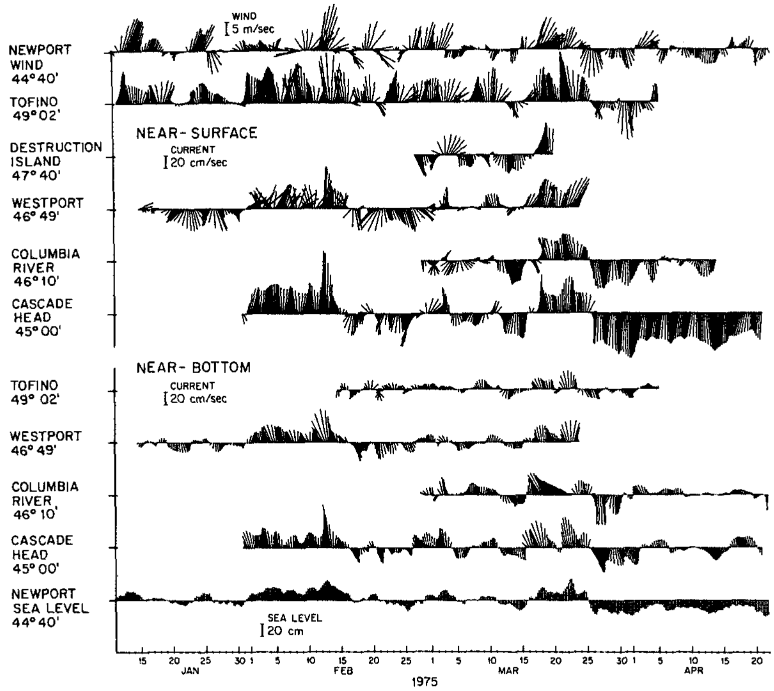

FIG. 2. Six-hourly vectors of Newport wind, near-surface and near-bottom current at locations from 49 to 45°N, and Newport sea level.

River plume. All exceptions but one (Cascade Head, T1) occur during the shortest period T3. Since the direction of the mid-water column flow is generally the same as that of the meters nearer the surface, although reduced in magnitude, we conclude that the mean seasonal surface Ekman layer may exceed 50 m in depth. This does not appear to be the case for the fluctuating flow (see Section 4).

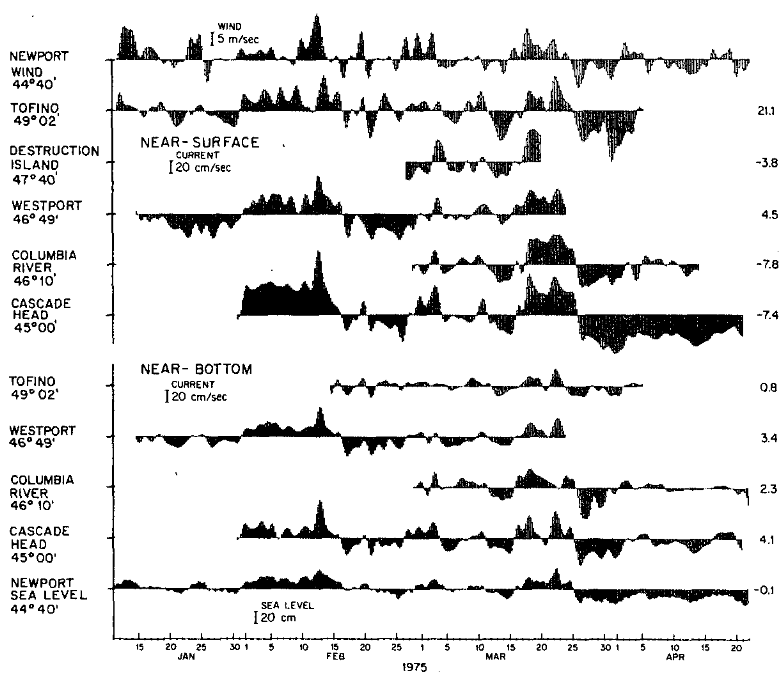

FIG. 3. Alongshore component of 6 h vectors of Newport wind, and of demeaned near-surface and near-bottom current at locations from 49 to 45°N, and Newport sea level. The number to the right of each series is its mean.

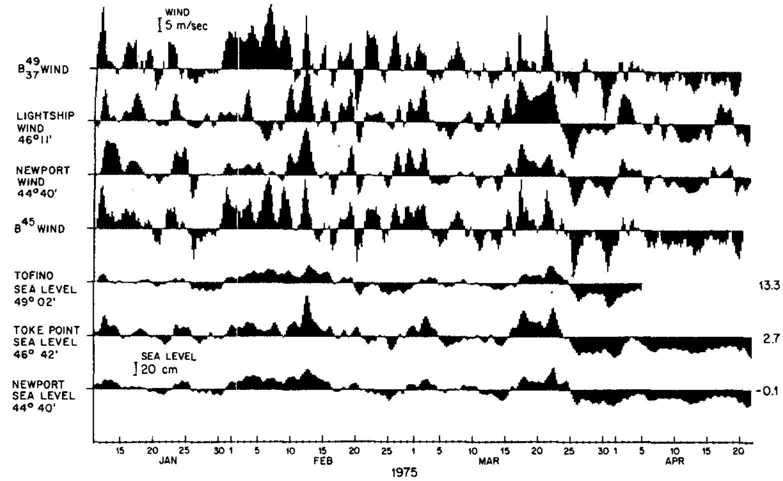

FIG. 4. Alongshore component of 6 h vectors of wind and demeaned sea level at locations from 49 to 45°N. The number to the right of each sea level series is its mean.

The mean flow everywhere south of Tofino is equatorward relative to that at Tofino (Table 2). Thus equatorward wind stress events south of Tofino appear to produce more current per unit stress than poleward events (Fig. 2). This situation is similar to that discussed by Scott and Csanady (1976) off the coast of Long Island in a water depth of 32 m. They show that the apparently anomalous southwestward flow at their location is caused by an alongshore pressure gradient force toward the southwest. A frictional equilibrium model provides a relatively good fit to their data.

Following their analysis, we write the alongshore momentum balance for the water column as

$$\tau_s - \tau_b = h \frac{\partial p}{\partial y} ,$$

where τ_s and τ_b are alongshore surface and bottom stress, respectively, h is water depth, and p is pressure. The sea level data in Table 3 do show a con-

TABLE 2. Basic statistics (cm s^{-1}) of the 6 h mid-shelf current records for three time periods: 31 January–23 March (T1, 52 days), 14 February–23 March (T2, 38 days), and 27 February–19 March (T3, 21 days).

	49°			48°	47°			46°			45°N			
LOCATION	Tofino			Destruction Island	Westport			Columbia River			Cascade Head			
DEPTH (m)	20	53	91	20	20	69	87	40	60	85	26	52	76	92
T1 $\bar{v}$	29.6				10.2	5.4	5.7				10.2	10.1	10.2	8.9
$\bar{u}$	2.7				2.9	0.5	-0.8				-0.2	-0.5	0.1	-1.3
σ_v	20.5				21.6	18.2	14.8				30.4	28.1	22.9	17.0
σ_u	7.8				12.5	5.1	4.9				5.8	4.6	3.4	3.6
σ_v/σ_u	2.6				1.7	3.6	3.0				5.3	6.1	6.7	4.7
T2 $\bar{v}$	24.5	9.2	2.7		3.7	-1.0	0.2				-1.5	-0.3	2.4	4.2
$\bar{u}$	3.6	0.8	-2.6		1.3	0.8	0.4				-1.2	-0.5	0.3	-0.7
σ_v	20.3	13.8	8.6		20.6	16.1	12.7				25.7	24.5	20.7	15.8
σ_u	7.8	5.2	3.6		11.2	4.8	4.2				6.1	5.0	3.6	3.7
σ_v/σ_u	2.6	2.6	2.4		1.8	3.4	3.0				4.2	4.9	5.8	4.2
T3 $\bar{v}$	21.7	8.9	3.0	-2.1	9.4	2.7	2.1	-6.3	-2.2	7.3	0.5	2.8	5.7	5.9
$\bar{u}$	4.4	1.5	-2.6	2.3	-0.8	-0.5	-0.0	2.5	0.9	-3.2	0.4	-0.4	0.1	-1.1
σ_v	19.3	12.1	7.5	22.2	14.5	12.4	10.0	18.5	16.5	12.9	24.1	23.0	19.8	15.5
σ_u	7.2	4.6	2.4	6.8	10.3	3.8	3.5	7.6	6.9	6.5	6.0	5.1	3.4	3.9
σ_v/σ_u	2.7	2.6	3.2	3.3	1.4	3.3	2.9	2.4	2.4	2.0	4.0	4.5	5.9	3.9

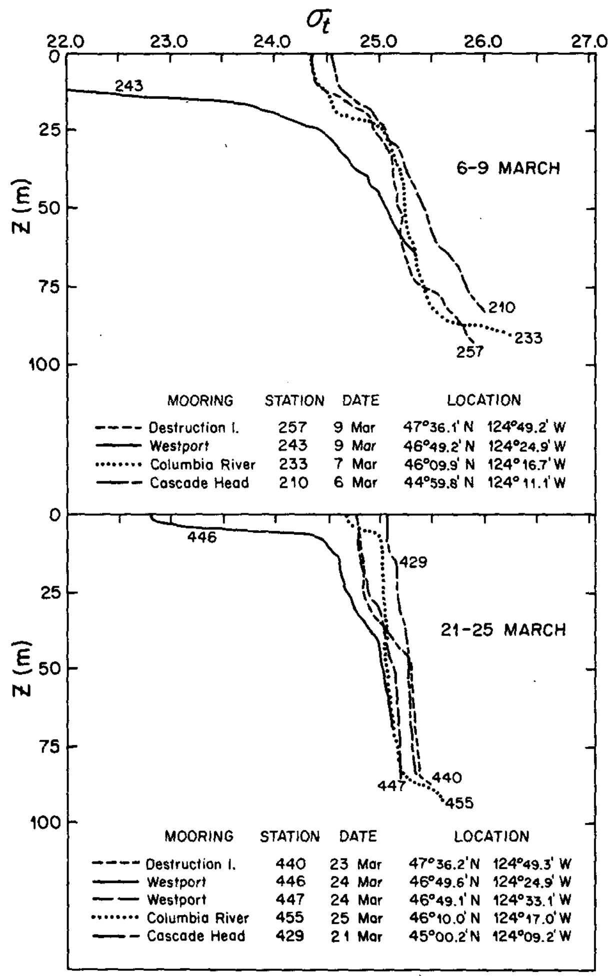

FIG. 5. Selected vertical profiles of σ_t taken in the vicinity of current meter moorings. The Westport mooring is equidistant from stations 446 and 447.

sistent slope downward toward the equator. However, these data are given relative to long term means. To obtain the absolute slope, we add long term means (relative to Newport) of 1.2 cm at Tofino and 0.6 cm at Toke Point as given by Pola and Hickey (1980). These means were estimated by relating long term averaged sea surface slope to long term averaged alongshore wind stress, a method which Chase (1979) has successfully applied to East Coast data. Thus, the absolute slope from Toke Point to Newport is 1.0×10^{-7}, which is roughly the same as the long-term February–March absolute slope given by Pola and Hickey (1980) for the region from 48 to 42°N.

With $h = 100$ m, $h\partial p/\partial y = 1.0$ dyn/cm^{-2}, $\tau_s = 1.0$ and $\tau_b = 0.09$ dyn cm^{-2}, using a square law, drag coefficients of 2.5×10^{-3},[1] and an average near-bottom current for T1 in the vicinity of Westport and Cascade Head. The bottom current was reduced by a factor of 0.77 to estimate velocities at the top of the log layer, using a bottom roughness scale for the region of 0.08 (Sternberg, personal communication) and the model of Businger and Arya (1974) (Long, personal communication). A linear relationship between bottom current and bottom stress as suggested by Scott and Csanady (1976) for low-frequency bottom currents may be more appropriate since the wind-driven fluctuations exceed the seasonal mean flow. Using the rms bottom current data in Table 2 (see Winant and Beardsley, 1979) we estimate a linear drag coefficient of

[1] 2.5×10^{-3} is used rather than the more conventional 1.3×10^{-3} to allow comparison with the model results of Hickey and Hamilton (1980). In their study, the larger drag coefficient was required to reproduce observed energy levels in alongshore current during this period.

TABLE 3. Basic statistics of the 6 h wind stress (τ_v, τ_u), wind (v, u), and sea level records for the period 31 January–23 March (T1, 52 days). Units are dyne cm^{-2}, m/s^{-1} and cm for wind stress, wind and sea level, respectively.

	WIND				SEA LEVEL		
	B^{49}_{37}	B^{45}	Lightship 46°	Newport 45°	Tofino 49°	Toke Point 47°	Newport 45°N
$\bar{\tau}_v$	1.9	1.2	1.7	0.8			
$\bar{\tau}_u$	0.4	0.4	-0.6	0.4			
$\bar{v}$	4.5	3.4	3.7	2.2	17.4	11.2	9.6
$\bar{u}$	1.2	1.6	-1.4	0.7			
σ_v	7.0	5.9	6.0	4.5	10.1	14.3	10.1
σ_u	5.1	5.1	7.2	3.5			
σ_v/σ_u	1.4	1.2	0.8	1.3			

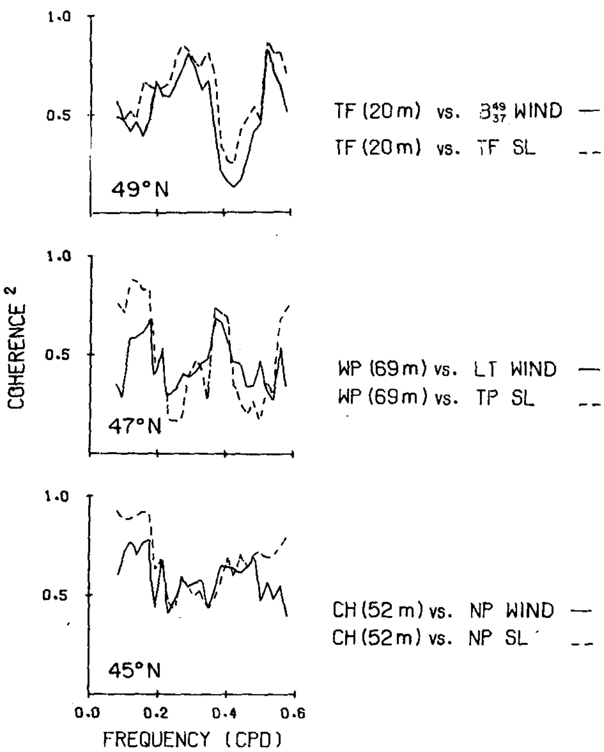

FIG. 6. Coherence-squared estimates between alongshore wind and alongshore mid-shelf current and between alongshore mid-shelf current and sea level at locations from 49 to 45°N. An estimate of 0.47 is significant at the 95% level (Koopmans, 1974).

32×10^{-3} cm s^{-1} which gives $\tau_b = 0.19$ dyne cm^{-2}. Thus, on the seasonal scale, the poleward wind force (τ_s/h) appears to be balanced by an equatorward pressure gradient force. The bottom retarding force is in the direction of the pressure gradient force but is relatively small.

The lack of an apparent equatorward mean flow at Tofino suggests that the alongshore pressure gradient force is less important to the momentum balance at that location. On the other hand, the sea level data give a slope between Toke Point and Tofino that is more than enough (2.6×10^{-7}) to provide a balance for the observed surface stress of 1.9 dyne cm^{-2}. Moreover, this large slope is similar to that which one obtains from seasonal sea level data between Clayoquot, B.C. (49°9′N, 125°55′W) and Neah Bay (~48°N) (Pattullo *et al.*, 1955). Although these latter data are not absolute, we note that the Pattullo *et al.* slope from Neah Bay (~48°N) to Crescent City (~42°N) for February–March is on the order of the value obtained with the present data set in the region south of Tofino. Using the Pattullo *et al.* data with some confidence then, we reach two important conclusions. First, of all the open-ocean stations from Yakutat (~60°N) to Crescent City, only Clayoquot (which is less than a mile from Tofino) has a maximum in January rather than December. Second, Clayoquot sea level is anomalously high from January to March in comparison with the other stations both to the north and the south: in January, sea level at Neah Bay (~48°N) and Prince Rupert (~54°N) are equal and in February and March, sea level slopes *down* toward the pole between these stations. I therefore conclude that sea level at Clayoquot and hence at Tofino is affected by freshwater effluent from the Strait of Juan de Fuca, which has a winter maximum driven by excess rainfall. Since the effluent should travel poleward along the isobaths on leaving the Strait, it seems reasonable that the sea surface slope and hence the pressure gradient force in the vicinity of Tofino is relatively small, which is consistent with the relative absence of equatorward mean flow in the region.

If the pressure gradient force does not balance the surface force at Tofino as the above discussion suggests, we might expect bottom friction to play a more important role at that location than at the more southern stations. Near-bottom currents at Tofino (Table 2) are not large enough to provide sufficient stress to retard the observed near-surface flow. However, the vertical shear in alongshore current between surface and mid-depths is an order of magnitude larger at Tofino than that at Cascade Head, presumably because of the relatively stronger pycnocline at Tofino. Then assuming that the pycnocline at Tofino retards the surface flow, we obtain

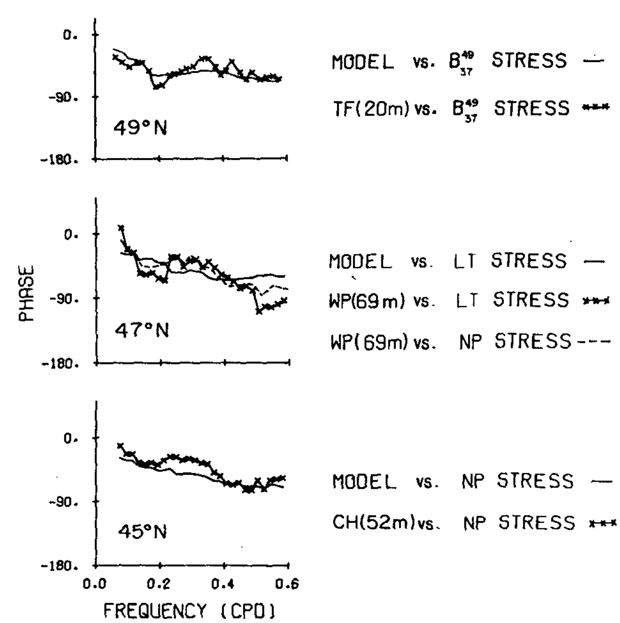

FIG. 7. Phase differences between alongshore wind stress and measured mid-shelf alongshore current and between alongshore wind stress and depth-averaged alongshore current predicted by the model of Hickey and Hamilton (1980) at locations from 49 to 45°N. A negative phase difference indicates that the first series in the title lags the second. Both surface and bottom stress were computed using a drag coefficient of 2.5×10^{-3}.

TABLE 4. Phase differences between alongshore wind (w) and alongshore current (v), between alongshore current and sea level, and between wind and cross-shelf current ($-u$), at selected frequencies at each location. A positive phase difference indicates that the first parameter in a pair leads the second. Error bars on phase differences are ±24° for a coherence estimate that is just significant at the 95% level (Jenkins and Watts, 1968).

		Tofino	Westport			Cascade Head			
	Frequency (cpd)	20 m	20 m	69 m	87 m	26 m	52 m	76 m	92 m
w/v	.12	62*	37	25	14*	28	28	24	18
	.18	77*	54	53	45	38	44	37	25
	.21	89	62*	83*	74	37	51	39	29
	.27	77	27*	46*	45	34	42	34	30
	.33	66	44*	45*	52	35	42	45	46
	.35	58	39*	31*	42	29*	28*	52	56
	.39	100*	56	45	55	44	45	58	56
	.49	101*	84	69*	69	73	85	76	65
	.53	73	110*	100*	101	89	93	90	79
SL/v	.12	-15	8	0	-17	- 11	-13	-18	-27
	.18	- 8	15	16	7	- 1	3	- 6	-18
	.21	31	-17*	14	8	- 4	10	- 2	-17
	.27	27	-58*	- 7*	-10	- 10*	- 1	-10	-17
	.33	21	10*	6*	7	- 7	1	3	7
	.35	17	32*	7*	21	- 16*	-10*	7	13
	.39	17*	35	17	28	- 10*	3	15	21
	.49	24	17	-14*	4*	25	27	27	20
	.53	17	1	-27*	-15*	20	24	27	20
w/-u	.12	79*	117*	59	22	-150*	11*	-14	-11
	.18	69*	128*	52	37	-110*	4*	-10*	0*
	.21	52*	159*	27	28	63*	41*	6*	27*
	.27	52*	117*	13*	0	34*	22*	6	30
	.33	111*	75*	-14	- 6	80*	44*	6	46
	.35	145*	79*	-15*	-10	91	53*	13	52*
	.39	124*	67*	-18*	- 8	28*	53*	31*	53
	.49	77*	125*	- 1*	20*	-62*	7*	11*	45
	.53	98*	114*	-90*	28*	-70*	3	1*	24

*Coherence not significant at 95% level

(with the linear law) $\tau_b = 1.4$ dyn cm^{-2} which is on the order of the observed surface stress of 1.9 dyne cm^{-2}.

4. The fluctuating flow

At each location the fluctuating current and sea level records are dominated by the local response to alongshore wind stress. This is suggested by the similarity between the alongshore current versus sea level coherence spectra and the alongshore current versus alongshore local wind coherence spectra (Fig. 6). Moreover, the phase difference between observed wind stress and current at each location is closely predicted by the depth-averaged local model of Hickey and Hamilton (1980) (Fig. 7). Consistency with this model implies that the alongshore momentum balance is essentially $\tau_s - \tau_b = h\partial v/\partial t$, where v is alongshore depth-averaged velocity and density is taken as unity. Note that at Tofino the observed phase difference has been corrected by an amount (18°) equal to the average phase difference by which Bakun wind precedes measured winds. The justification for this correction is that the average phase difference between B^{45} and Newport wind is 18° ± 10°. Phases of Bakun winds may be biased on the early side by, for example, data from the offshore Weather Station PAPA.

TABLE 5. Correlation coefficients between pairs of variables separated alongshore, calculated for T2 (38 days). Both the value of the coefficient at zero lag (r) and at the lag which gave maximum correlation (r_M) are given. A positive lag of n indicates that the first variable in a given pair leads the second by $6n$ h. The 90% significance level is 0.51 (Hald, 1952); the number of degrees of freedom was taken as the total time period divided by the autocorrelation scale.

	v vs. v				u vs. u		
	Separation (Km)	r	r_M	Lag	r	r_M	Lag
Near-Surface Currents							
Westport vs. Cascade Head	200	.80	.80	0	-.12	.15	8
Tofino vs. Cascade Head	480	.71	.71	0	-.05	.09	-8
Tofino vs. Westport	290	.58	.58	0	-.19	.14	8
Mid-Depth Currents							
Westport vs. Cascade Head	200	.88	.88	0	-.02	.20	8
Tofino vs. Cascade Head	480	.76	.76	0	.36	.49	1
Tofino vs. Westport	290	.69	.69	1	.06	.14	2
Near-Bottom Currents							
Westport vs. Cascade Head	200	.85	.87	-1	.54	.54	0
Tofino vs. Cascade Head	480	.72	.72	0	.15	.27	1
Tofino vs. Westport	290	.68	.70	1	.08	.26	-7
Wind							
Lightship vs. Newport	170	.80	.80	0	.56	.68	-1
B^{49}_{37} vs. Newport	520	.54	.64	1	.22	.26	-2
B^{49}_{37} vs. Lightship	360	.41	.51	2	.12	.33	7
B^{49}_{37} vs. B^{45}	520	.83	.83	0	.51	.52	-1
Sea Level							
Toke Point vs. Newport	230	.87	.87	0			
Tofino vs. Newport	520	.81	.81	0			
Tofino vs. Toke Point	310	.69	.69	0			

The percent of the alongshore current variance accounted for by the model is 70% at Cascade Head, 50% at Westport using Newport stress and 50% at Tofino. The difference in percentages probably reflects the quality of the local wind data rather than the degree of local response.

The model phase lag ϕ of v with respect to τ_s, increases as ω increases, consistent with the observations at all three locations (Fig. 7 and Table 4). This suggests that bottom friction becomes less important as frequency increases. The poleward increase in wind stress magnitude (~ a factor of 2 between 45 and 49°N) results in friction being more important (ϕ is smaller) at Tofino than Cascade Head at most frequencies outside the band 0.18–0.34 cpd. The value of ϕ given by the model at high frequencies (~0.5 cpd) at Westport is also smaller than that at Cascade Head, and is significantly smaller than the value given by the observations at Westport. A much closer fit between observed and predicted values of ϕ for the higher frequencies at Westport is obtained when Newport wind stress is used instead of Lightship wind stress (Fig. 7). It is likely that the Lightship wind data are influenced by local orographic effects.

Phase differences between sea level and the alongshore current are generally small (Table 4), as expected for the local model. Moreover, the phase differences between alongshore wind and cross-shelf velocity are also roughly consistent with local forcing: the near-surface currents have a much larger phase difference with the wind (approaching the 180° expected for a classical surface Ekman layer) and the deeper currents are more in phase with the wind, reflecting the 0° expected for a classical bottom Ekman layer.

a. Alongshore coherence

There is considerable alongshore coherence in the alongshore current and sea level fields (Table 5 and Fig. 3). Empirical orthogonal eigenfunctions calculated using mid-depth alongshore current at Westport (mid-shelf station only) and Cascade Head (mid-shelf and outer shelf) and near-surface[2] current at Tofino (mid-shelf and outer shelf) for the period 31 January–23 March show that 80% of the variance

[2] Mixing depths of current meters is justified by the high vertical coherence.

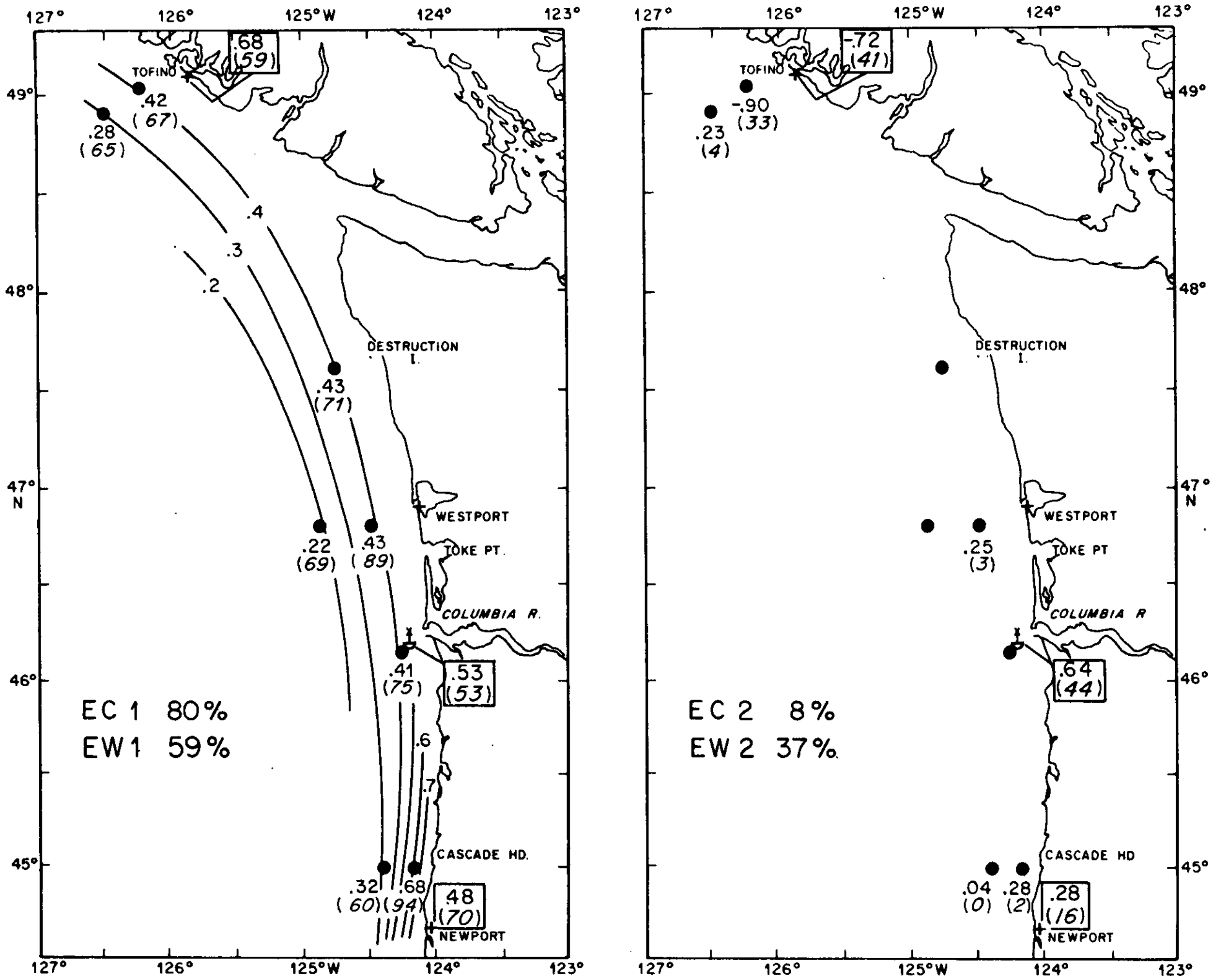

FIG. 8. Amplitude of first and second current (EC1, EC2) and wind (EW1, EW2) empirical orthogonal eigenfunctions and, in brackets, the percent of variance accounted for by the eigenfunction at each location.

can be explained by an eigenfunction (EC1) whose amplitude is of the same sign at each location (Fig. 8). Note that amplitudes at Destruction Island (near-surface) and Westport on the outer shelf (mid-depth) and Columbia River (mid-depth) were interpolated from values for the period 27 February–19 March, when data were available at all locations. The amplitude decreases north of Cascade Head and with distance offshore at all locations. The eigenfunction accounts for 67, 89 and 94% of the variance at mid-shelf locations near 49, 47 and 45°N, and 65, 69 and 60% of the variance at outer shelf locations at the three latitudes. Comparing coherence spectra between pairs of sea level stations separated alongshore (Fig. 10) with those of EC1 versus sea level at the three latitudes demonstrates that EC1 adequately represents alongshore fluctuations that are coherent over the largest (~500 km) scale at all frequencies.

Empirical orthogonal eigenfunctions calculated for the three wind stations show that 59% of the variance is contained in the first eigenfunction (EW1, Fig. 8). The fact that EW1 is significantly coherent with EC1 at all frequencies (Fig. 9) suggests that the alongshore coherence in the current field is a result of large coherence scales in the wind field.

In spite of the significant alongshore coherence expressed by the first current and wind eigenfunctions, the differences among current versus sea level coherence spectra at the three locations (Fig. 6) show that shorter scale structure in the current and sea level fields is also important. The primary alongshore differences are a relative maximum in local coherence and in energy near 0.3 cpd at Tofino and a relative minimum near 0.45 cpd, in comparison with stations farther south (Figs. 6 and 11). The wind spectra also reflect these differences (Fig. 11). The second current eigenfunction (EC2), which accounts for 8% of the total variance, but 33% of the variance at Tofino (and only 3 and 2% at mid-shelf

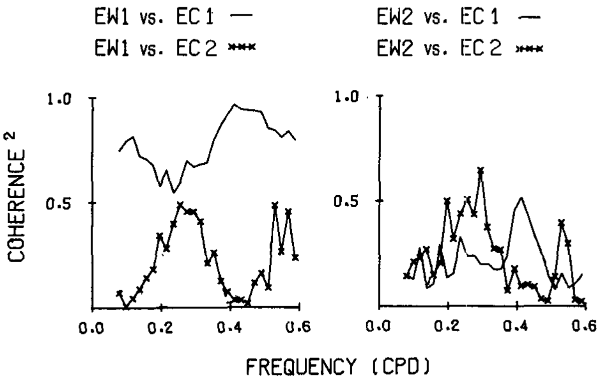

FIG. 9. Coherence-squared estimates between wind (EW1, EW2) and current (EC1, EC2) eigenfunctions. An estimate of 0.47 is significant at the 95% level (Koopmans, 1974).

at Westport and Cascade Head, respectively), describes some of this structure (Fig. 8) and is significantly coherent only with Tofino sea level (Fig. 10). The spatial distribution of EC2 at the midshelf stations is the same as that of the second wind eigenfunction EW2 (which accounts for 37% of the wind variance), and EC2 and EW2 are significantly coherent in the band 0.20–0.35 cpd (Fig. 9) where the greatest alongshore differences occurred. As expected, EC2 is significantly coherent only with B^{49}_{37} in this band (Fig. 10). This suggests that the small-scale current features are related to small-scale wind features, adding strength to the hypothesis of local wind forcing.

Since the winds are significantly correlated over an alongshore separation of about 500 km, significant correlation between the cross-shelf components of current at different locations might be expected. Table 5 shows that the cross-shelf components of near-surface and of mid-depth currents are not significantly correlated between any of the locations. Near-bottom currents at Westport and Cascade Head are significantly correlated at the 90% level.

b. Direction of travel

An important result from this winter–spring data set is that a unique direction of travel for current and sea level fluctuations cannot be prescribed at any frequency when all the data is included and equally weighted (Table 6). For example, local alongshore wind directions (Newport versus Lightship) are often opposite to those of computed winds (B^{45} vs B^{49}_{37}); and directions determined from sea level data are often opposite to those determined from current meter data.

One definite conclusion that can be made, however, is that alongshore current and sea level phase differences whose coherences are significant at the 95% level and which indicate poleward propagation are too small to provide the appropriate phase speed (~400 km day^{-1}) for free shelf waves. This gives at least weak support to the local forcing hypothesis. We now ask whether there is any stronger support. To be consistent with a local response to a traveling disturbance, alongshore phase differences between fluctuations must be determined solely by the τ/v phase difference at each location and the alongshore phase difference of the forcing itself. Between Cascade Head and Westport, phase differences at all frequencies are generally small (less than the error bars for a 95% significant coherence) indicating an almost simultaneous response at all frequencies. Phase differences are generally larger between Tofino and the southern stations (~40°), but except at frequencies less than 0.21 cpd and at 0.53 cpd, sea level and current fluctuations travel in opposite directions. Nevertheless, we note that in two of the three frequency bands where alongshore coherence was significant over the 500 km scale (see Fig. 10), the data are reasonably consistent with local wind forcing: at 0.39 cpd, sea level and Bakun wind phase differences are all small and show equatorward travel (the current phase differences are all associated with very low coherences and are consequently discounted). At 0.53 cpd, where

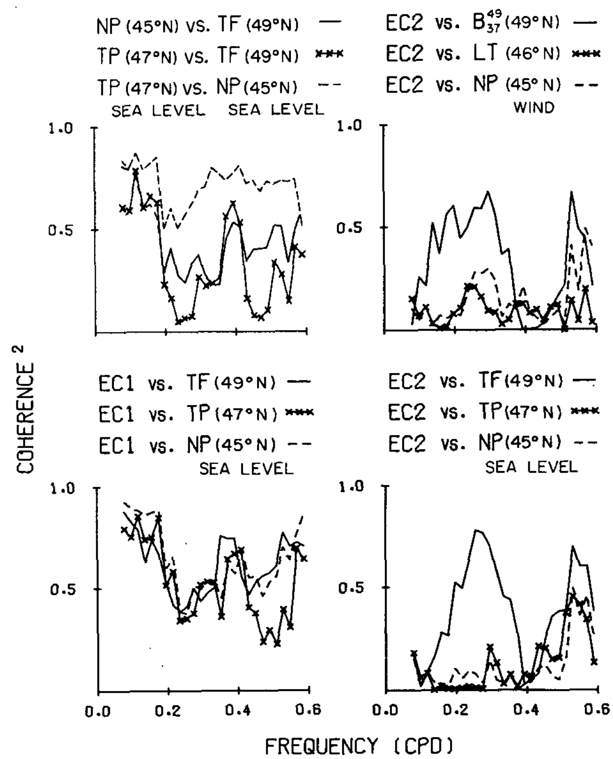

FIG. 10. Coherence-squared estimates between pairs of sea level stations separated alongshore and between current eigenfunctions (EC1, EC2) and wind and sea level at locations from 49 to 45°N. An estimate of 0.47 is significant at the 95% level (Koopmans, 1974).

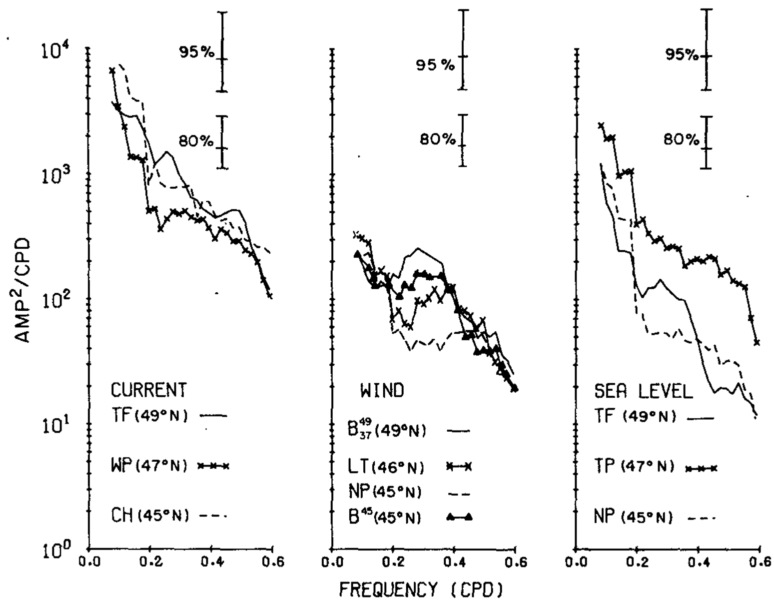

FIG. 11. Spectra of measured alongshore mid-shelf, near-surface current, alongshore wind and sea level at locations from 49 to 45°N. Each estimate has 14 degrees of freedom. Confidence intervals are based on Koopmans (1974).

TABLE. 6. Phase difference between pairs of wind, sea level and current records separated alongshore, at selected frequencies. Error bars on phase differences are ±24° for a coherence squared estimate that is just significant at the 95% level (Jenkins and Watts, 1968). The 20 m current at Tofino has been used to represent currents at all depths at that location. A negative phase difference indicates equatorward propagation. Arrows at the top indicate the frequencies of strongest alongshore coherence over the large (~500 km) scale (see Fig. 10).

Frequency (cpd)	↓ .12	.18	.21	.27	.33	↓ .39	.49	↓ .53
B^{45} vs. B^{49}_{37}	-18	-15	-19	-22	-20	-12	-17	-17
Newport vs. Lightship Wind	3	-2	-16	-5	-10	2	10	5
Newport vs. Toke Point SL	-11	-2	-3	5	5	-2	22	34
Cascade Head 26 vs. Westport 20	9	13	-9	5*	16*	26*	18	14*
Cascade Head 52 vs. Westport 69	1	9	8	23	17	9	2	11
Cascade Head 92 vs. Westport 87	5	20	23	24	6	9	9	10
Tofino vs. Newport SL	18	31	-42*	-54*	-40*	-16*	-53*	-51*
Tofino vs. Cascade Head 26	13*	11*	9*	35*	33*	45*	49*	-36*
Tofino vs. Cascade Head 52	8	10*	9*	36*	38*	33*	19*	-39*
Tofino vs. Cascade Head 92	26	32	25*	45*	12*	42*	35*	-40
Tofino vs. Toke Point SL	30	31	-15*	-63*	-38*	-2	-80	-95*
Tofino vs. Westport 20	6	-3	2	19	43*	42*	70*	-94*
Tofino vs. Westport 69	8	-3	14	6	25	45*	16*	-52
Tofino vs. Westport 87	19	12	-6	10	26*	40*	26*	-43

*Coherence not significant at 95% level

current phase differences are dramatically different (~100°) from those at lower frequencies, the data also suggest a wind-forced response to an equatorward traveling disturbance. Although alongshore wind phase differences (17°) are smaller than alongshore current and sea level differences (~40°), the remaining phase difference is at least partially accounted for by the less frictional current response to wind forcing at Cascade Head in comparison with Tofino as shown in Fig. 7. Considering the 3° averages used for Bakun winds, any closer agreement in phase differences could only be fortuitous.

In the third frequency band where alongshore coherence was significant (0.12 cpd), current and sea level fluctuations generally travel in the same direction, opposing the computed wind, but traveling with the measured wind. Although it might be tempting to conclude that these data suggest free waves, in agreement with Wang and Mooer's (1977) low frequency signals during summer, 1973, the phase differences are about half as large as required. On the other hand, we note that Bakun wind data at frequencies below 0.2 cpd are poorly coherent with local winds (NP vs $B^{45} \sim 0.4$ and NP vs $B_{37}^{49} \sim 0.02$) and thus somewhat suspect. We also note that the phase difference between Lightship and Newport wind, at 0.12 cpd, if extrapolated over 500 km, would make the data roughly consistent with a local response to a traveling disturbance.

5. Discussion and Conclusions

This paper investigates the alongshore coherence in current and sea level fluctuations over scales of 200–500 km on the Pacific Northwest continental shelf during late winter and early spring. In particular, the following is shown:

1) Alongshore coherence in sea level and in the alongshore component of current is significant over scales of 200 to 500 km; alongshore coherence in the cross-shelf component of current is significant at the 95% level only for bottom currents and only over the 200 km scale.

2) Local wind forcing dominates the response at each of the three locations studied; this was shown in several ways: (i) by illustrating the similarity of alongshore current versus sea level coherence spectra and alongshore current versus local wind coherence spectra, (ii) by comparing local phase relationships with those predicted by the one-dimensional model of Hickey and Hamilton (1980) (essentially a balance between local acceleration and surface and bottom stress), and (iii) by demonstrating that alongshore differences in the energy distribution of the wind field are reflected in alongshore differences in the energy distribution of current and sea level fields.

3) The alongshore coherence in currents and sea level reflects alongshore coherence in the forcing. Many of the disturbances in the alongshore wind field had scales exceeding 500 km. These large-scale wind features, represented by an empirical orthogonal eigenfunction that accounts for 59% of the total variance in the alongshore wind field, were significantly coherent at all frequencies with the first alongshore current eigenfunction, which accounts for 94, 89 and 67% of the variance at mid-shelf near Cascade Head (~45°N), Westport (~47°N) and Tofino (~49°N), respectively. Alongshore coherence in current and sea level was significantly reduced in the band where alongshore current and wind fields (as represented by their second eigenfunctions) demonstrated significant alongshore structure. The second current and wind eigenfunctions, which both changed sign between Tofino and southern Washington, were significantly coherent in a band near 0.3 cpd. The second current eigenfunction contributed 33% to mid-shelf fluctuations at Tofino and less than 5% to fluctuations at all other locations.

4) Alongshore phase differences are too small to provide consistency with free wave propagation. On the other hand, in three frequency bands where alongshore coherence in wind, current and sea level fluctuations was strongest, the phase differences are consistent with a local response to a traveling wind disturbance. At the lowest frequency (0.12 cpd) fluctuations traveled poleward between all locations; whereas at 0.39 and 0.53 cpd, fluctuations traveled equatorward between Tofino and stations to the south, arriving essentially simultaneously off southern Washington and Oregon. At 0.53 cpd, the modeled local response was slower (less frictional) at Cascade Head than at Tofino due to the weaker wind stress at Cascade Head, consistent with the fact that alongshore current phase differences were larger than alongshore wind phase differences.

5) The importance of local forcing decreases significantly offshore; the percent of variance accounted for by the first current eigenfunction was typically on the order of 65% at the shelf edge.

6) The seasonal mean cross-shelf velocities demonstrate a single-celled Ekman-layer response.

7) The seasonal mean alongshore velocities are consistent with the existence of an alongshore pressure gradient force, positive toward the equator, at least in the region south of Vancouver Island. South of Tofino, where poleward wind force (τ_s/h) and equatorward pressure gradient force ($-\partial p/\partial y$) provide the vertically averaged momentum balance, near-surface and mid-water column currents are more equatorward than at Tofino, where it appears that the retarding force of the pycnocline rather than the pressure gradient force balances the applied wind force.

The existence of an alongshore pressure gradient has important implications on the fluctuating flow and should be included in any model [cf., Bennett and Magnell (1979) for the New Jersey coast]. The result, of course, for a sea surface sloping down toward the equator, is effectively to reduce the forcing for poleward wind stress events and enhance it for equatorward events, producing a mean equatorward flow relative to that which would be expected from the wind stress alone. The system can no longer be described as two-dimensional, although modifications to a two-dimensional model are relatively simple. Investigation of these relationships on both event and seasonal time scales and of the role of $\int_0^h fudz$ in the dynamical balance is continuing as a separate project.

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REFERENCES

Bakun, A., 1975: Daily and weekly upwelling indices, west coast of North America, 1967–73. U.S. Department of Commerce. NOAA Tech. Rep. 16 NMFS SSRF-693, 114 pp.

Bennett, J. R., and B. A. Magnell, 1979: A dynamical analysis of currents near the New Jersey Coast. *J. Geophy. Res.*, **84**, 1164–1175.

Businger, J. A., and S. P. S. Arya, 1974: Height of the mixed layer in the stably stratified planetary boundary layer. *Advances in Geophysics*, Vol. 18A, Academic Press, 73–92.

Chase, R. R. P., 1979: The coastal longshore pressure gradient: temporal variations and driving mechanisms. *J. Geophys. Res.*, **84**, 4898–4904.

Cutchin, D. L., and R. L. Smith, 1973: Continental shelf waves: Low-frequency variations in sea level and currents over the Oregon continental shelf. *J. Phys. Oceanogr.*, **3**, 73–82.

Gilbert, W. E., A. Huyer, E. D. Barton and R. L. Smith, 1976: Physical oceanographic observations off the Oregon Coast, 1975: WISP and UP-75. School of Oceanography, Oregon State University, Data Report 64, Ref. 76-4, 189 pp.

Hald, A., 1952: *Statistical Theory with Engineering Applications*. Wiley, 783 pp.

Hickey, B. M., 1981: Temporal and spatial variability of the California Undercurrent off Washington during summer 1972. Submitted to *J. Mar. Res.*

——, and P. Hamilton, 1980: A spin-up model as a diagnostic tool for interpretation of current and density measurements on the continental shelf of the Pacific Northwest. *J. Phys. Oceanogr.*, **10**, 12–24.

Hsueh, Y., and C. Y. Lee, 1978: A hindcast of barotropic response over the Oregon-Washingtron continental shelf during the summer of 1972. *J. Phys. Oceanogr.*, **8**, 799–810.

Huyer, A., J. Gagnon and S. Huggett, 1976: Observations from current meters moored over the continental shelf off Vancouver Island, 28 November 1974 to 8 April 1975, and related oceanographic and meteorological data. Tech. Rep. No. 4, Environment Canada, Fisheries and Marine Service, 54 pp.

——, B. M. Hickey, J. D. Smith, R. L. Smith and R. D. Pillsbury, 1975: Alongshore coherence at low frequencies in currents observed over the continental shelf off Oregon and Washington. *J. Geophys. Res.*, **80**, 3495–3505.

Jenkins, G. M., and D. G. Watts, 1968: *Spectral Analysis and its Applications*. Holden-Day, 525 pp.

Koopmans, L. H., 1974: *The Spectral Analysis of Time Series*. Academic Press, 366 pp.

Kundu, P. K., and J. S. Allen, 1976: Some three-dimensional characteristics of the low-frequency current fluctuations near the Pacific coast. *J. Phys. Oceanogr.*, **6**, 181–199.

Pattullo, J., W. Munk, R. Revelle and E. Strong, 1955: The seasonal oscillation in sea level. *J. Mar. Res.*, **14**, 88–155.

Pola, N., and B. M. Hickey, 1980: The seasonal alongshore pressure gradient along the west coast of the United States. *Trans. Amer. Geophys. Union*, **61**, 980.

Scott, J. T., and G. T. Csanady, 1976: Nearshore currents off Long Island. *J. Geophys. Res.*, **81**, 5401–5409.

Smith, J. D., B. Hickey and J. Beck, 1976: Observations from moored current meters on the Washington Continental shelf from February 1971–February 1974. University of Washington, Department of Oceanography, Spec. Rep. No. 65, 383 pp.

Wang, D. P., and C. N. K. Mooers, 1977: Long coastal trapped waves off the west coast of the United States, Summer 1973. *J. Phys. Oceanogr.*, **7**, 856–864.

Winant, C. D., and R. C. Beardsley, 1979: A comparison of some shallow wind-driven currents. *J. Phys. Oceanogr.*, **9**, 218–220.

Wright, D. G., and L. A. Mysak, 1977: Coastal trapped waves, with application to the northeast Pacific Ocean. *Atmosphere*, **15**, 141–150.