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Littoral Cell Response to Interannual Climatic Forcing 1983-1987 on the Central Oregon Coast, USA

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ABSTRACT

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Longshore distributions of beach sand (1983-1987) in a 17.2 km long subcell (Seal Rocks-Yachats Point) of the central Oregon coast have been studied to document interannual variability of longshore transport resulting from and following the anomalous 1982-83 north Pacific climatic event. Some 4-8 $\times$ 10^6 m^3 of beach sand was displaced northward from the 7.4 km long southern end of the headland bounded subcell during the 1982-83 winter. The 1982-83 volume of interannual longshore displacement (5-11 $\times$ 10^2 m^3 per meter of shoreline distance) from the southern 7.4 km of the cell exceeds a reported annual seasonal exchange (across-shore) from an adjacent cell by at least a factor of 5.

The northward displacement of beach sand in 1982-83 resulted from (1) a southward 10°-15° latitude (1,000-1,500 km) shift of the winter (Dec.-Feb.) geostrophic wind guide (1014-1016 mb), *i.e.*, a proxy for the seasonal storm tracks, relative to a 16 year mean of 50-55° N, and (2) an above average (but not exceptional) energy of winter wave climate, based on weekly and daily mean significant wave heights ($H_{1/3}$). An El Niño-Southern Oscillation (ENSO) related elevation of mean sea level (some 30 cm above a 16 year mean) might have facilitated offshore transport of the beach sand during the winter period, but it is not considered to have been important in the longshore redistributions of beach sand. A two year delay in the southward return of the northward displaced sand corresponds to winter geostrophic wind guides of very high latitude (55-65° N). Historical records of erosion and accretion of beaches and the Alsea Bay spit within the subcell indicate that the 1983-87 cycle of sand redistribution in central Oregon was the most extensive in the last 24 years (period of available records).

ADDITIONAL INDEX WORDS: *Littoral, longshore transport, beach erosion, wave climate, sea level, ENSO, Oregon.*

INTRODUCTION

Observed variations in the direction of incident wave attack (northwest-to-southwest) along the central Oregon coast indicate the potential for reversals of longshore sand transport over time scales ranging from seasons to hours (KULM and BYRNE, 1966; BEACH and STERNBERG, 1987). However, a long term balance between the opposing directions of transport is indicated by (1) an equal distribution of bay spit orientations to the north and south, and (2) the relatively symmetric deposition of beach sand on opposite sides of harbor jetties (KOMAR *et al.*, 1976). Numerous headlands along the modern coast provide boundaries to longshore transport and divide the coast into cells, possibly ranging from 10 km to 100 km in length (CHESSER and PETERSON, 1987). Estimates of short-term fluctuations in longshore sand distributions within the cells are needed to predict near-term conditions of shoreline instability along this headland bounded coastline.

While a zero net littoral drift might prevail over time scales of decades within the major cells, estimates of interannual longshore transport rates are needed to predict shoreline instabilities that occur over shorter periods. For example, significant shoreline erosion has recently occurred along some segments of the Oregon coast due to an apparent short-term displacement of sand (1983-1986) from the southern end of many littoral cells. Extensive displacements of sand from these beaches

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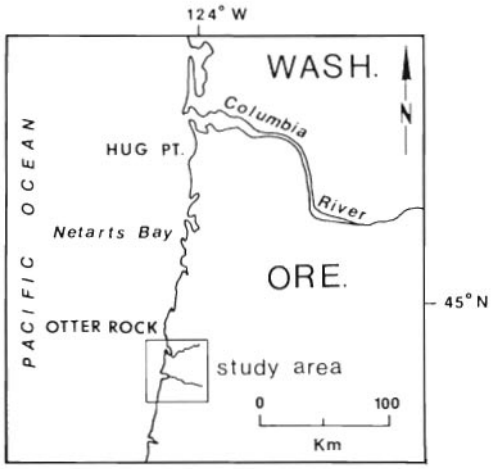


Figure 1. Locations of the study area and several small cells of the north-central Oregon coast that experienced interannual sand displacement associated with the 1982-1983 north Pacific climatic event.

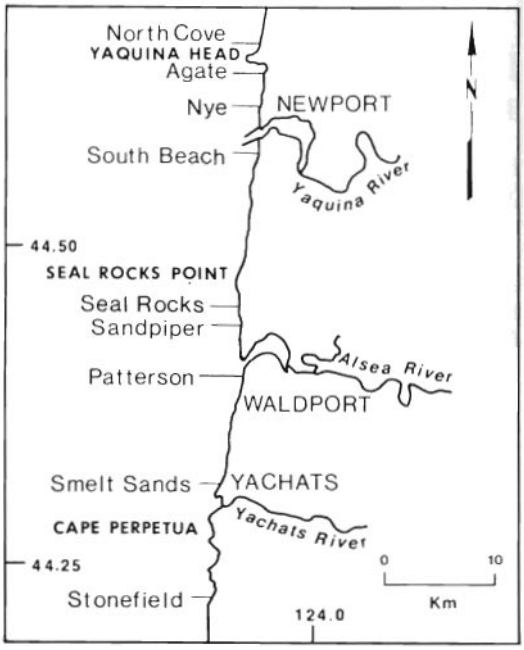


Figure 2. Coastal features of the study area including (1) major headlands (Yaquina Head and Cape Perpetua), (2) rocky points (Sea Rocks and Yachats) (3) estuaries (Yaquina Bay and Alsea Bay) and (4) coastal communities (Newport, Waldport and Yachats). Beach names represent sites of sand sample collection (see Table 1).

(PETERSON, *et al.*, 1986; KOMAR, 1986) resulted from atypical climatic conditions which coincided with the 1982-83 El Niño-Southern Oscillation (ENSO) event (HUYER *et al.*, 1983). The longshore movement of beach sand that occurred during this unusual climatic event provides an unique opportunity to measure interannual rates of longshore sand transport on the north Pacific coast. While studies of seasonal across-shore transport have been conducted in the study area (FOX and DAVIS, 1978) no measures of short-term longshore transport have previously been reported.

In this paper we report on the anomalous 1982-83 displacement of sand and its four year recovery along a beach segment of the central Oregon coast (Figure 1). We estimate the volume and rate of anomalous sand transport and relate anomalous local seacliff retreat to the observed event of sand displacement. We use recent and historical tidal inlet positions to document previous interannual variations in longshore sand distributions within this small subcell. Finally, the northward displacement of beach sand in 1983 and its eventual return in 1987 within the study cell are compared to longer records of seasonal wave height, directional wind-wave forcing, storm track proxies, and seasonal mean sea level during the winters of 1972-1987. The results of this investigation should have relevance to much of the Pacific Northwest region, where anomalous beach erosion following the 1982-83 climatic event has been reported from northernmost California (TUTTLE, 1987), central Oregon (KOMAR, 1986, 1989) and southern Washington (PETERSON and BINNEY, 1988).

BACKGROUND

The study area is located along a 43 km shoreline of broad sandy beaches (greater than 100 m in width) that are terminated to the north and south by basalt headlands (Figure 2). Yaquina Head projects 1.7 km seaward of the adjacent shoreline and clearly bounds littoral transport at the northern end of the study cell. It has not been previously established whether the smaller Yachats Point and Cape Perpetua headlands terminate longshore transport at the southern end of the study area. Low seacliffs are cut into uplifted Pleistocene terraces that

range in height from 5 m to 30 m above sea level. Historic shoreline retreat in the study area is variable and is reported to have averaged between 0.1 and 0.3 m yr^{-1} over a 34 year period (SMITH, 1978). While the estimated shoreline retreat rates are small by comparison to some barrier shorelines of the eastern and gulf coasts of the United States (MAY *et al.*, 1983), it is the apparent stability of the shorelines in the Pacific Northwest region that has, in part, enticed development out to the precipice of many seacliffs.

One of earliest studies of seacliff erosion on the Oregon coast (BYRNNE, 1964) was performed at Jumpoff Joe, located near Nye Beach at the northern end of the study area (Figure 2). Slumping and seacliff failures along several kilometers of the coastline adjacent to the Jumpoff Joe site are related to ongoing slip along an oceanward dipping bedding plane (BYRNNE, 1964). A vertical seacliff along this area is maintained by wave erosion of the slump toe. By comparison, seacliff erosion within the southern half of the study area generally occurs over much smaller length scales (100's meters), being related episodic wave attack during winter storms (FOX and DAVIS, 1978). Regionally synchronous erosin of the shoreline within this cell has not been previously reported. The eroding seacliffs are thought to be sources of beach sand to the study cell, while two estuaries, Yaquina Bay and Alsea Bay, serve as coastal sand sinks. While no river sand is thought to be escaping from the tidally dominated Yaquina Bay (KULM and BYRNE, 1966), some river sand is thought to be escaping from the fluvially dominated Alsea Bay (PETERSON *et al.*, 1982).

An increased frequency of large storm waves (KOMAR, 1986) and anomalously high values of monthly sea levels, 30 cm above 10 year means, (HUYER *et al.*, 1983) were recorded along the central Oregon coast during the winter of 1982-83. These climatic and oceanographic coincidences are reported to have caused the extensive beach erosion observed during the 1982-83 winter (KOMAR, 1986). Significantly, an anomalous sand accretion at some beaches, located immediately south of headlands at northern cell boundaries, indicated a northward sand displacement during the 1982-83 winter event. Such a northward displacement of beach sand apparently forced the seaward portion of the tidal ebb channel at the mouth of Alsea Bay to the north in late 1983 (JACKSON and ROSENFELD, 1987). The recurved inlet channel deepened the water immediately seaward of the spit, and subsequent wave attack finally eroded the southern end of the spit in the winter of 1985.

METHODS

The recoveries of the Alsea Bay spit and shorelines to the south of the bay mouth during the several years (1985-1988) following the 1982-83 displacement event are the focus of this report. Unfortunately, no permanently established profiles were established for this littoral cell or for any other headland bounded cells of the Oregon coast prior to 1982-83. The significance of the 1982-83 sand displacement event, in terms of ongoing coastal erosion in Oregon, was not fully recognized until the winter of 1985 and has become most apparent in some cells within the last several years (KOMAR, 1986; PETERSON and BINNEY, 1988; KOMAR, 1989). This study was initiated in part to utilize existing survey data and scaled photographs of the seacliffs and exposed wave cut platforms that were taken by commercial contractors between 1983 and 1985 (Eckman Creek Quarry; unpublished data). This limited survey data provides the pre-recovery conditions of the study area beaches (exposed wave-cut platform), which we have used to measure against the present (post-recovery) conditions of the accreted beaches.

In addition to the existing survey data (above), the study area was monitored for longshore sand redistribution (1985-1988) by several methods. Aerial photographs of the entire study area were taken by these authors and by the State of Oregon, Department of Transportation, in 1985 and 1986. The Alsea Bay tidal inlet (a potentially sensitive indicator of longshore sand movement) was monitored for cross-sectional area on a monthly basis (winter 1985-to-spring 1987) and quarter annual basis (summer 1987 -to- present). Inlet surveys were conducted with a depth fathometer, and the boat positions were tracked by an EDM theodolite total station mounted over a USC&GS benchmark (JACKSON and ROSENFELD, 1987).

Post-recovery beach profiles were established (June 1987) at approximately evenly spaced intervals along the study cell after beach sand

volumes (berm heights) reached pre-1982-83 summer levels (as observed by beach front residents). Beach profiles (June 1987) were surveyed by stadia and transit method during an extreme low tide series. Repeated visits (fall 1987 and July 1988) by these authors to the southern profile sites of the study area showed no substantial changes in backshore sand elevations (relative to permanent reference points) after the June 1987 profiling work. A single period of beach surveying during the summer of 1987 is justified by the limited data on the foreshore platform elevations in the study area. The uncertainties of the foreshore platform profiles should account for the greatest errors in the estimates of the sand volume displacements that occurred between 1983 and 1987.

It is important to know whether the shoreline under study is a closed system with regards to potential sources or sinks of beach sand. A total of nine beach sites within the study area were sampled in March, 1984 for mineral and textural analyses of the beach sediments (Figure 2 and 3). Heavy minerals in the sand samples were petrographically analyzed for two pyroxene minerals, hypersthene and augite. These mineral phases are similar in shape and density, but have different sources (PETERSON *et al.*, 1982). At least 200 colored pyroxene grains were counted per sample to establish normalized pyroxene ratios of hypersthene: hypersthene + augite. A test of the pyroxene ratio variability from beach sands with a common source was performed to establish effects of localized mineral sorting. A group of seven beach samples located 25-30 km south of Cape Perpetua, and having a common sand source (Umpqua River) showed a standard deviation of 0.03 about a mean of 0.43. The sample grain size distributions (bulk sand) were also analyzed by the standard sieving technique (FOLK, 1980). Mean grain size values of the beach sand samples were calculated from moment statistics methods.

RESULTS

Beach Sand Composition

The measured pyroxene ratios of beach sands from within the study cell (Figure 3) show that the sands north of Yachats Point (pyroxene ratio 0.24-0.26) differ greatly from beach sands south of Cape Perpetua (pyroxene ratio > 4.0). It is therefore apparent that the Yachats and Cape Perpetua headlands do provide an effective southern barrier to littoral sand mixing. A slight difference in sand mineralogy also exists on either side of Seal Rocks, as shown by southern pyroxene ratios of 0.24-0.26 and by northern pyroxene ratios of 0.31-0.34. The slightly higher augite content of the sands south of Seal Rocks might reflect a minor supply of Alsea River sand (high in augite) to the adjacent beaches as suggested by PETERSON *et al.* (1982). Seal Rocks is a relatively small point with a seaward projection of only several hundred meters (Figure 4). The small compositional variation between beach sands on either side of Seal Rocks indicates some restriction to mixing around this rocky shoreline projection, but it does not exclude the possibility of limited sand bypassing around the small barrier.

Grain size analyses of beach sediments in the study area further confirm the headland controlled boundaries to longshore transport (Figure 3). Gravel lag deposits were found at beaches immediately north of the two major headlands, Yaquina Head and Yachats Point. Shorelines just north of the gravel lags and also north of the Seal Rocks Point were completely stripped of beach sand, thereby exposing the wave-cut beach platform throughout the years of 1984 and 1985. The loss of beach sand and the exposure of underlying gravel lags and/or the beach platform reflects the downdrift starvation of sand that occurred north of transport barriers during the previous winter of 1983. The apparent sand trapping by Seal Rocks Point during the 1983 displacement event indicates that the larger littoral cell between Yaquina Head and Cape Perpetua can be divided into two subcells on either side of this rocky point. We use the 'subcell' designation since the effectiveness of Seal Rocks in bounding longshore transport over long time scales is not known.

Shoreline Erosion and Accretion

The best documented effects of the study area response to the 1982-83 sand redistribution event are from the southern half of the subcell that is located south of Seal Rocks. Extensive

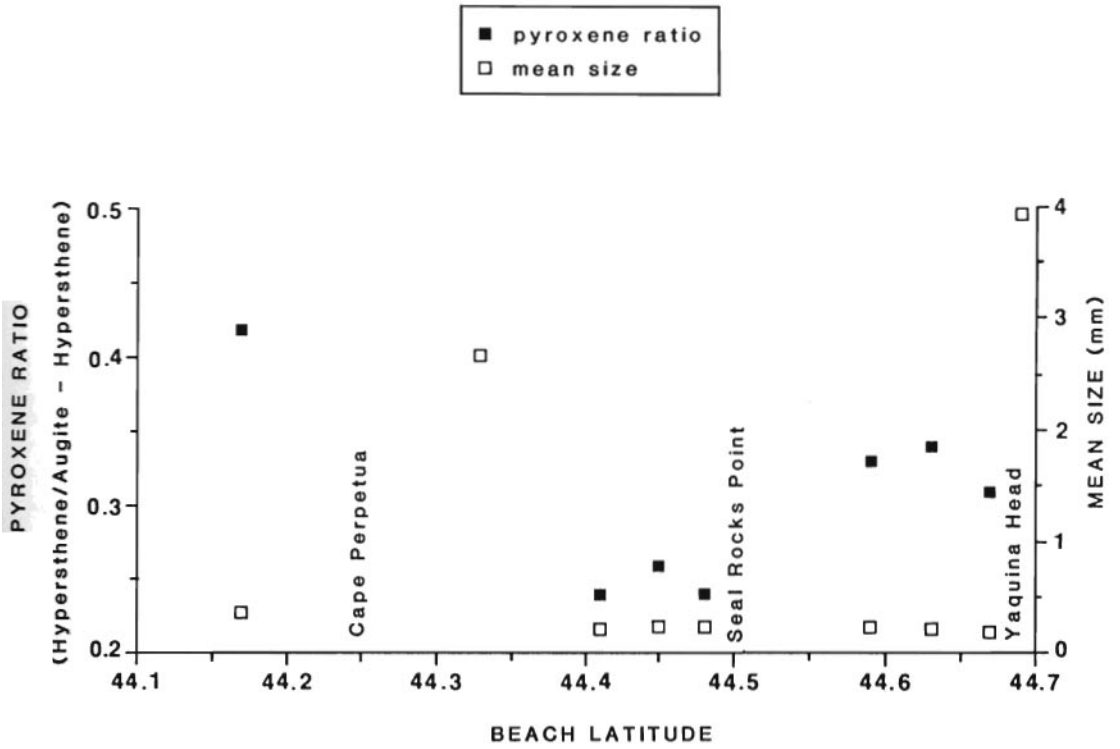
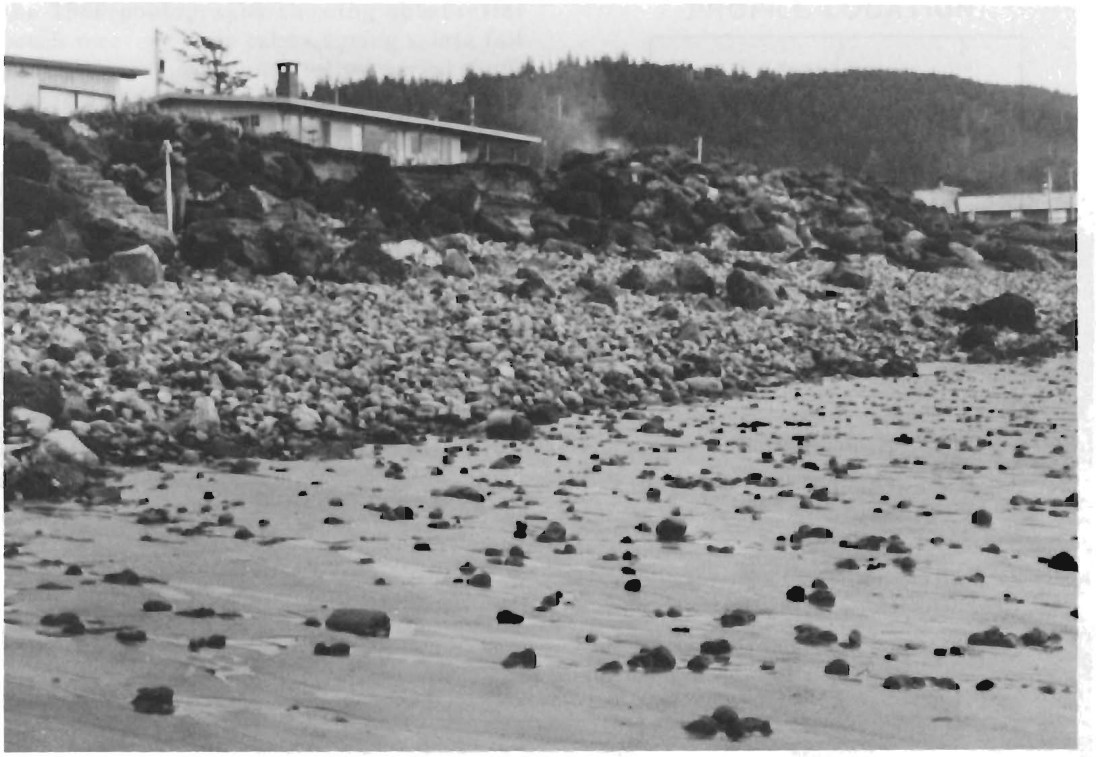


Figure 3. Plots of pyroxene ratio and grain size versus sample latitude (see Figure 2) show natural boundaries to longshore transport. Normalized pyroxene ratios are based on hypersthene / hypersthene + augite. Mean grain size values are based on standard sieving analyses at 0.5 phi intervals.

placement of riprap was performed from 1983 to 1986 along selected sites between 1 and 7 km north of Yachats Point in an effort to protect eroding coastal properties. The maximum erosion of the natural (unprotected) low terraces (3-6 m above MSL) occurred in the winters of 1984 and 1985, some one to two years after the initial sand displacement event in 1983. Surveys and photographic records taken in association with the riprap installations establish retreat rates of 0-3 m y^{-1} for unprotected terrace segments at six localities (1-7 km north of Yachats Point) during the 1983-86 period. Seacliff retreat generally decreased with increasing distance north of the southern end of the Seal Rocks subcell. The changes in terrace lithology and the proximity of protective riprap structures greatly influenced local variability of the seacliff erosion. However, evidence of sea cliff retreat (active slumps and basal undercutting) was generally observed throughout the 1-7 km distance north of Yachats Point.

The 1983-85 seacliff erosion north of Yachats Point was caused by a complete loss of the beach sand buffer from 1983-1985, permitting direct wave attack on the poorly consolidated terrace deposits. Photographs of two different beach sites, located 2 km and 3 km north of Yachats Point, were taken in 1984, and were rephotographed again in 1986 (Figure 5a, b) in conjunction with the riprap projects. These photographs demonstrate the initial loss and eventual recovery of sand in the southern part of the Seal Rocks subcell. The magnitude of the sand displacement is particularly evident in these photographs which were taken in contrasting seasons of across-shore sand transport. For example, the 1984 photographs showing maximum sand loss were taken during a late spring period (May 18), usually a period of

Figure 4. Oblique aerial photograph (view to the north) of Yaquina Head (horizon), Seal Rocks Point (midground) and anomalous sand accretion (foreground), taken at low tide in June of 1985. Unusual foredune development (white sand) is apparent just south of Seal Rocks Point.



onshore (landward) sand transport. In contrast, the 1986 photographs showing substantial beach recovery were taken during a late fall period (November 25), normally a period of offshore (seaward) sand transport. The first winter storms of the winter season typically initiate the offshore transport of beach sand in late October. Additional photographs from these sites show that the exposed beach platform was still evident by the summer of 1985. The multiyear displacement of sand from the southern one half of the subcell was clearly not the result of seasonal cycles of across shore transport.

Evidence of the northward displacement of sand in the Seal Rocks subcell is also demonstrated in oblique aerial photographs of the northern part of the subcell, taken in the spring of 1985. Anomalous foredune accretion is apparent from 0 to 1 km south of Seal Rocks Point (Figure 4), and there is no evidence of erosion (vertical scarps) in the western edge of the small dune field. A similar, but larger, dune field is also reported to have developed south of Yaquina Head during the same time interval (KOMAR, 1986). Field observations in 1985-1987 confirmed that anomalous sand accretion 1-3 km south of the Seal Rocks Point protected the base of the seacliff from winter surf erosion for 2-3 years following the 1982-83 sand displacement event. Young conifers, several years in age, colonized the weathering debris and dune sand along the foot of the northern seacliffs, which were protected from storm surf by high beach berms during the winters of 1984 and 1985.

The protection of the seacliffs at the northern end of the subcell contrast sharply with the active erosion of the seacliffs at the southern end of the subcell during the same period (see above). Subsequent erosion of the anomalous dune field at the northern end of the subcell began in the winter of 1986, as shown in aerial photographs. This erosion reflected the initial phase of beach sand returning south to the southern beaches of the subcell.

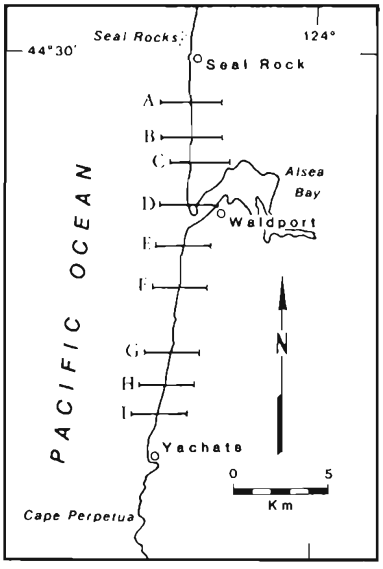


Figure 6. Locations of nine beach profiles measured in June 1987. Profile locations F, G, H and I were selected on the basis of exposed beach platform surveys conducted prior to riprap installations during 1984 and 1985.

Beach Profiles

Beach profiles at nine sites were surveyed by transit and stadia method in the Seal Rocks subcell during an extreme low-tide series in June 1987. The seaward ends of the profiles were terminated near the low-low water point, as estimated by time and tide tables. The profile locations (Figure 6) were selected on the basis of (1) representative beach widths observed in 1986 aerial photographs and (2) exposed beach platform surveys completed in the winters of 1984 and 1985 during construction of shoreline protective structures. June 1987 profile slopes ranged from 0.020 in the northern transects to 0.025 in the southernmost transects (Figure 7). A small scarp in profile B, at 50 m seaward of the seacliff, denotes the past winter's excavation of the remaining berm deposit discussed above. Nearshore bars produce minor topographic highs towards the seaward end of profiles C, D, E, G and H, but have small effect on

Figure 5a (*Page 93*). Photographs of two beach segments located 2 km (a) and 3 km (b) north of Yachats Point, a south bounding headland, showing contrasting sand volumes in late spring, May 18, 1984 (upper photographs) and in late fall, Nov. 25, 1986 (lower photographs). Backshore sand accumulation at these sites reached the maximum pre-1983 elevation, near the top of the riprap barrier, by the summer of 1987.

Figure 5b (*Facing page*). Photographs of two beach segments located 2 km (a) and 3 km (b) north of Yachats Point, a south bounding headland, showing contrasting sand volumes in late spring, May 18, 1984 (upper photographs) and in late fall, Nov. 25, 1986 (lower photographs). Backshore sand accumulation at these sites reached the maximum pre-1983 elevation, near the top of the riprap barrier, by the summer of 1987.

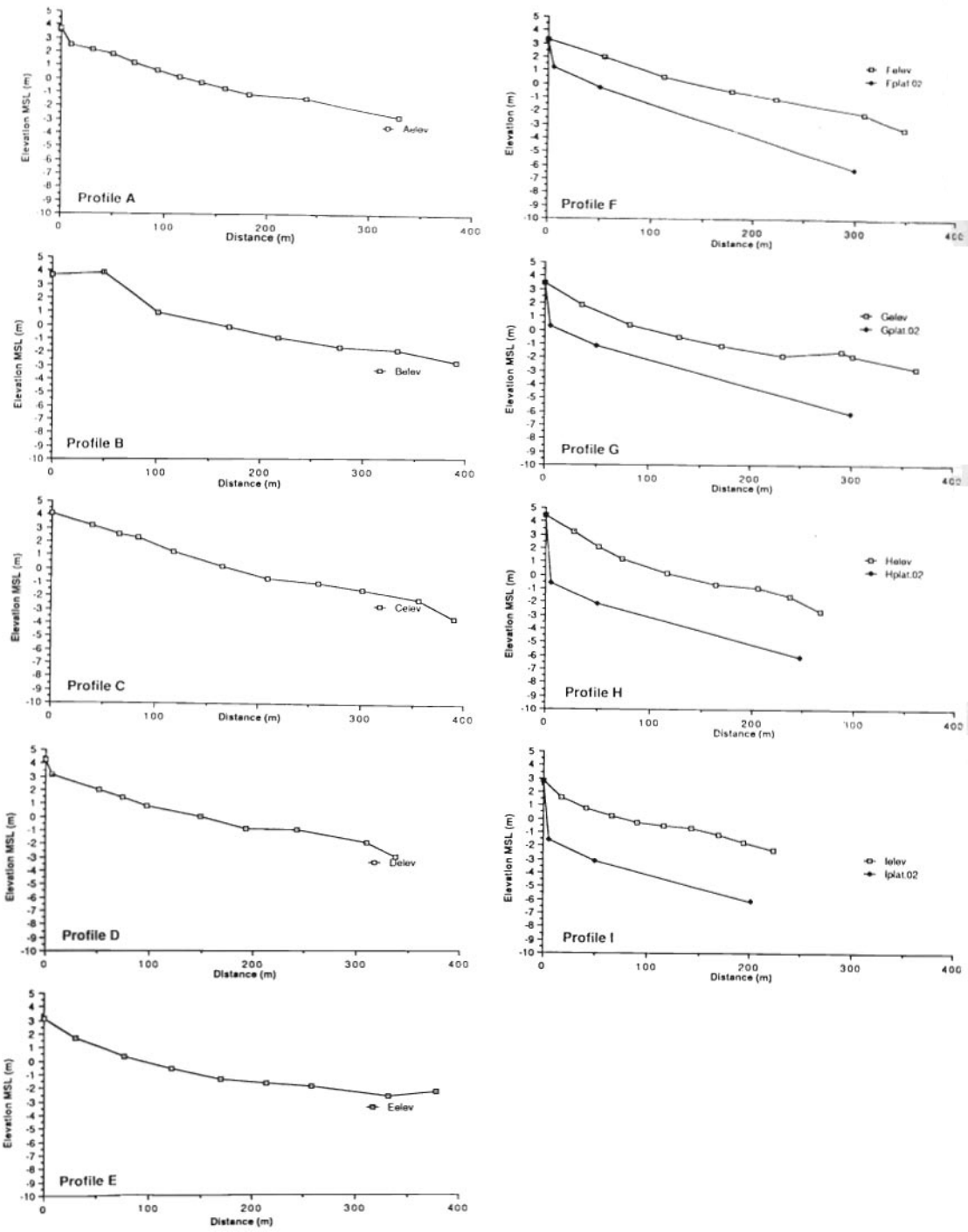


Figure 7. Summer (1987) beach sand profiles and exposed (1983) platform profiles (F, G, H, I) based on known backshore platform elevations and on extrapolated foreshore platform elevations assuming 0.02 gradients for the foreshore platforms.

the average beach slopes. The early summer profiles of 1987 show little or no significant variation in either beach slope or elevation above mean sea level from north to south. These surface profiles are assumed to approximate equilibrium conditions of sand distribution along the subcell.

A continuous exposure of the beach platform between profiles F and I during the winters of 1983-85 provides an erosional surface level with which to compare later periods of sand accretion, *i.e.*, the June 1987 beach profiles. Active wave scouring of the exposed wave cut platform was observed during extreme low tides in March of 1984 to occur out to a distance of 300 m seaward of the seacliff near profiles F and G, and out to a distance of 200 m seaward of the seacliff at profile I. It was not possible to establish whether the platform was exposed or covered by sand at locations seaward of these points, due to increasing water depth in the surfzone.

The elevations of the exposed platform at profiles F, G, H and I were surveyed in to registered bench marks or photographed against known vertical scales prior to riprap installation in the winters of 1984 and 1985. Platform elevations of profiles F-1 were measured at points several meters seaward of the foot of the seacliff and at about 50 m seaward of the seacliff. Backshore platform gradients of the surveyed sites equaled 0.03 (Figure 7). Unfortunately, foreshore platform gradients at profiles F-I were not surveyed. Later efforts to trench and probe down to the beach platform underlying the accumulated sands (at least 3-4 m thick) in June of 1987 were unsuccessful. The foreshore gradients are assumed to fall between (1) the measured backshore slopes of 0.03 and (2) the slopes of the inner-shelf, averaging 0.01 from 0 to 20 m water depths (U.S. Coastal and Geodetic Survey Chart 1308N-22). Foreshore platform gradients measured just north of Yaquina Head in 1983 averaged 0.02 (PETERSON *et al.*, 1986). The foreshore platform surfaces shown in profiles F, G, H and I (Figure 7) are extrapolated from the known backshore elevations (survey data) using an assumed gradient of 0.02.

Estimates of Beach Sand Displacement

Sand recovery in the southernmost beaches of the study area began after the spring of 1985 (see photographs of exposed platform in Figures 5a, b), and it reached pre-1983 summer berm heights by the summer of 1987 as reported by ocean frontage residents. Spot checks of berm height at profile sites I and H during the fall of 1987 and summer of 1988 did not indicate any significant increases in sand accretion at these sites after the 1987 profile period. Estimates of the total volume of sand displaced in 1982-83 and recovered by June 1987 are calculated from profile cross-sectional areas. Known platform elevations and gradients of 0.03 are used to construct the backshore cross-sectional areas to 50 m seaward of the seacliff (Figure 7). Foreshore platform gradients of 0.01, 0.02 and 0.03 are used to extrapolate the foreshore platform profiles to 200-300 m seaward of the seacliff (Table 1). A comparison of the profile cross-sectional areas based on the 0.02 foreshore platform gradients shows relatively little difference between the four profile locations at sites F (1050 m^2), G (1130 m^2), H (1190 m^2) and I (880 m^2). Shorter cross-sections in the most southern profiles (H, I) are roughly balanced by thinner cross-sections in the more northern profiles (F, G).

Table 1. *Beach Profile Data, Seal Rocks Subcell.*

	Beach Profiles			
	F	G	H	I
Distance From Seal Rocks (km)	10.1	13.7	15.5	17.1
Mid-Point Lengths (km)	2.0	2.7	1.7	1.0
Cross-Sectional Areas (m^2)				
Backshore Gradients (0.03)				
and Foreshore Gradients of				
(0.01)	424	507	793	660
(0.02)	736	819	993	772
(0.03)	1049	1132	1193	884
Segment Volumes ($\times 10^6$ m^3)				
For Backshore Gradients (0.03)				
and Foreshore Gradients of				
(0.01)	0.85	1.37	1.35	0.66
(0.02)	1.47	2.21	1.69	0.77
(0.03)	2.10	3.06	2.03	0.88

The total volume of sand displaced from the southern 7.4 km of the Seal Rocks subcell is estimated to be 6 $\times$ 10^6 m^3, based on a 0.02 value for the foreshore platform gradients (Figure 7, Table 1). Minimum and maximum estimates of sand volume displacement are calculated to be 4 $\times$ 10^6 m^3 (0.01 foreshore gradients) and 8 $\times$ 10^6 m^3 (0.03 foreshore gradients). Normalizing the total volume of sand displacement (4-8 $\times$ 10^6 m^3) by the length of the sand stripped

shoreline (7.4 km) yields a value of 5-11 $\times$ 10^2 m^3 of displaced sand volume per linear meter of shoreline. A monthly rate of longshore volume transport during the five month winter storm period of 1982-83 is estimated to be 2-4 $\times$ 10^2 m^3 per meter longshore per month. This estimate is based on the assumptions that 4-8 $\times$ 10^6 m^3 of sand was displaced northward over 3.7 km, *i.e.*, the mid-point of the sand stripped shoreline (total distance 7.4 km) during a five month winter period (November 1982-to-March 1983).

Alsea Bay Tidal Inlet Changes

Erosion of the southern end of the Alsea Bay spit in the fall of 1985 has been linked to the anomalous northward displacement of sand which occurred two years earlier in 1983 (KOMAR, 1986; JACKSON and ROSENFELD, 1987). Following the erosion of the spit, the tidal inlet shallowed to the north and deepened to the south, indicating a return of sand to the northern inlet area during the years 1986 and 1987. A series of cross channel surveys, taken by these authors between 1985 and 1989, demonstrates the narrowing of the inlet cross-sectional area from 2050 m^2 to about 660 m^2 during the late spring of 1987, and the maintenance of the narrow inlet morphology (cross-sectional area $<$ 700 m^2) through the spring of 1988 (see panels D-F in Figure 8; inlet cross-sections in Figure 9). Variable river discharge, with monthly means reaching 0-10% of the estuarine tidal prism, had no visible effect on the inlet width between 1985 and 1987. In contrast, the narrowing of the inlet to pre-1983 widths coincides with the maximum return of beach sand to the southern beaches of the study area observed during the summer of 1987.

In an effort to identify cycles of longshore sand movement within the Seal Rocks subcell, an analysis of past inlet-spit morphologies has been performed from available aerial photographs taken between 1961 and 1985. Spit surface areas above approximate low water levels (MLW) were measured south of a reference line drawn due west from the southern end of the Alsea Bay bridge (Table 2). The results of the spit area analysis are shown in Figure 10 and demonstrate that the 1985 truncation was by far the most extensive erosional event of the spit during the last two and one half decades. The 1985 spit surface area totaled 54,500 m^2 less than the mean surface area of 55,200 m^2. Three additional events of significant spit erosion occurred in 1962 (21,900 m^2 below mean area), 1971 (30,000 m^2 below mean area) and in 1978 (22,000 m^2 below mean area).

Although the Alsea Bay spit-inlet configuration is maintained by tidal circulation (BOLEY, 1973), the relative importance of river discharge in adding to the ebb flow and thereby altering the spit morphology (surface area) is also evaluated here. A linear regression between mean annual river discharge (U.S.G.S. 1961-1985) and spit area for the 1961 to 1985 period shows a poor least squares correlation ($R = 0.36$) between the spit configuration and the mean annual river discharge (Table 2). Interannual cycles of spit accretion and erosion at Alsea Bay do not show a significant influence from interannual variation of river discharge. Therefore they are assumed to be primarily forced by changes in the longshore distribution of littoral sand at the bay mouth.

DISCUSSION

Interannual Climatic Forcing

The 1982-83 northward displacement of beach sand on the Oregon coast was not forced by a single catastrophic storm event, but rather was the net result of anomalous climatic and oceanographic conditions throughout the winter season. The full return of beach sand to the southern end of the Seal Rocks subcell did not occur until approximately four years (1987) after the northward displacement event in 1982-83. Furthermore, there was no evidence of southward sand transport during the first two years (1984-1985) after the initial northward displacement. The climatic and oceanographic variables that are considered to have had potentially the greatest effect on the interannual variability of longshore sand transport are incident wave energy, angle of wave attack and possibly sea level (KOMAR, 1983; DEAN, 1983). The relative importances of these three factors in controlling the 1983-87 cycle of beach sand redistribution are discussed below.

Seasonal Wave Height

Wave height and period are measured over ten minute intervals every six hours with an

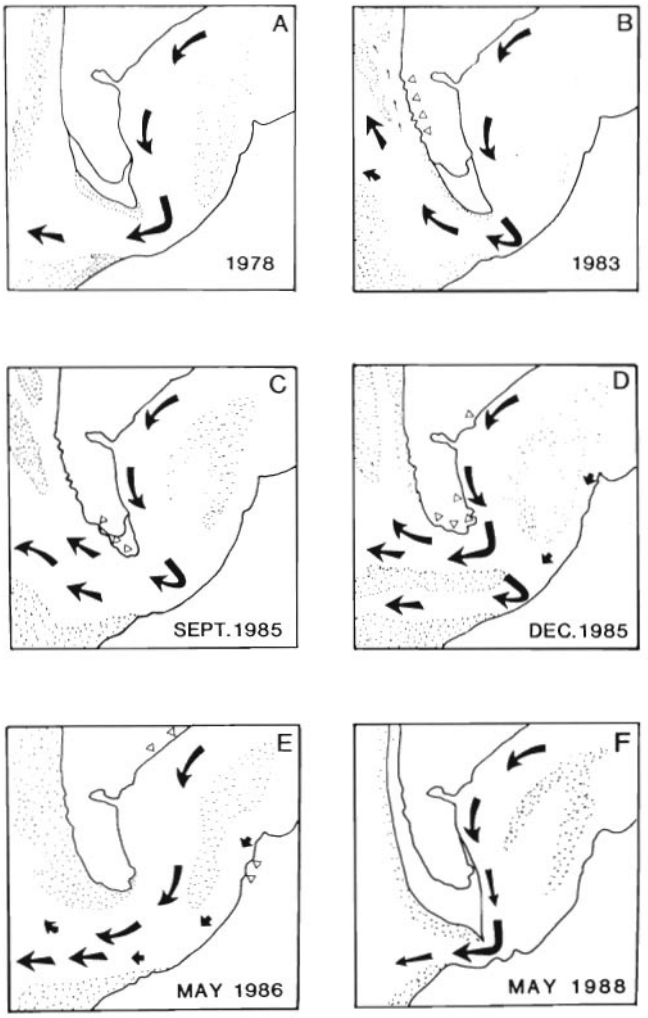


Figure 8. Sequences of inlet channel movement and corresponding spit erosion and accretion in the mouth of Alsea Bay (1978-1988). Black arrows indicate ebb-current flow, and triangles denote areas of shoreline erosion. See text for description of events A-F. Spit morphologies and current patterns were analyzed from aerial photographs and bathymetric surveys conducted between 1985 and 1988.

analog seismic recording system at Newport, Oregon (CREECH, 1981). A plot of winter seasonal averages of mean significant wave height ($H_{1/3}$) for the years 1972-1981 and 1983 are shown in Figure 11. The average wave height during the 1982-83 winter, *e.g.* $H_{1/3}$ 2.6 m (Dec.-Feb.) and $H_{1/3}$ of 2.4 m (Nov.-Mar.) was high, but not anomalous relative to corresponding 10 year means (1972-81) of 2.45 ± 0.17 (Dec.-Feb.) and 2.40 ± 0.18 (Nov.-Mar.) as shown in Figure 13. In terms of frequency of extreme wave conditions, the weekly maxima of $H_{1/3}$ at Newport reached 5.0-5.5 on four occasions, and reached 6.0 m once during the 1982-83 winter period (GARROW, 1985). By comparison, eight out of the previous ten winters had at least four weekly maxima of $H_{1/3}$ topping 5.0 m (CREECH, 1981). Daily $H_{1/3}$ maxima exceeded 5.0 m some ten times during the 1982-83 winter, while six of the previous ten years had at least eight events of daily $H_{1/3}$ maxima exceeding 5.0 m.

The 1982-83 winter period did experience sev-

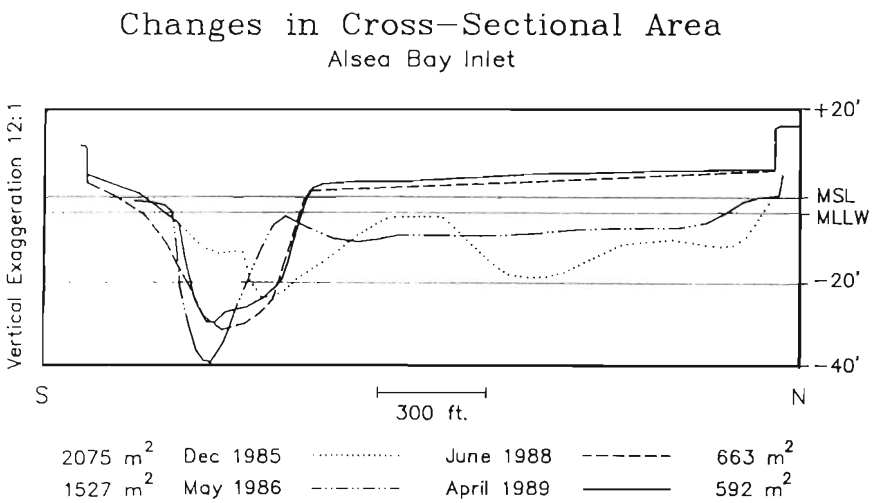


Figure 9. Changes in cross-sectional area of Alsea Bay inlet between 1985 and 1989. Graph shows changes in inlet shape: table presents corresponding measurements of cross-sectional area established by inlet surveys.

Table 2. *Alsea Bay Spit Areas and River Discharge.*

Water Year	Relative Spit Area (m^2)	Mean Annual Discharge (m^3s^{-1})
1961	66643	50.40
1962	33321	36.00
1965	64912	34.92
1968	89681	49.42
1971	24769	57.88
1973	121283	46.90
1976	47830	28.22
1978	33310	26.35
1984	66620	46.73
1985	768	34.19

A least squares linear regression between Mean Annual Discharge (x) and corresponding Relative Spit Area (y) is of the form: y = 1178x +6494 and shows a poor correlation (R = 0.36) between the two variables.

eral events of very large breaking waves, H_b = 7 m (KOMAR, 1986) and a slightly above average frequency of $H_{1/3}$ maxima exceeding 5.0 m. However, unlike central California (SEYMOUR *et al.*, 1985), the comparisons of significant wave heights in central Oregon from the winter of 1982-83 and from the previous ten years do not indicate an extreme condition of incident wave energy in Oregon during the winter of 1982-83. It does not appear that the winter wave energy alone can account for the unusual displacement of sand from the southern end of the study cell during the winter of 1982-83. Significant wave height data from Newport has yet to be compiled and analyzed for the years of 1982 and 1984-1988.

Latitudes of Seasonal Storm Tracks

Directional wave data are not supplied by the Newport micro-seismic recorder. Relative directions of winter wave approach must be approximated from other climatic records which indicate relative wind-wave directions. Such proxies for relative wave direction should be averaged over the winter months of maximum storm activity. Unfortunately, an extensive buoy station grid does not exist offshore the Pacific Northwest coast, so precise directional wind-wave analysis is not currently possible. One method of establishing the relative direction of onshore wind-wave forcing in the northeast Pacific is based on Sea Level Pressure (SLP) charts of the north Pacific. Seasonal winter averages (December-February) of the north Pacific SLP have been discussed by Emery and Hamilton (1985) for the years 1947-1982, and additional seasonal SLP charts have been supplied to us by the NOAA Climate Analysis Center for the winters 1982-1987.

A series of seasonal SLP charts for the years 1972 to 1987 shows that an anomalous southeastward displacement of the Aleutian low pressure area (Figure 12a-f) coincides with the

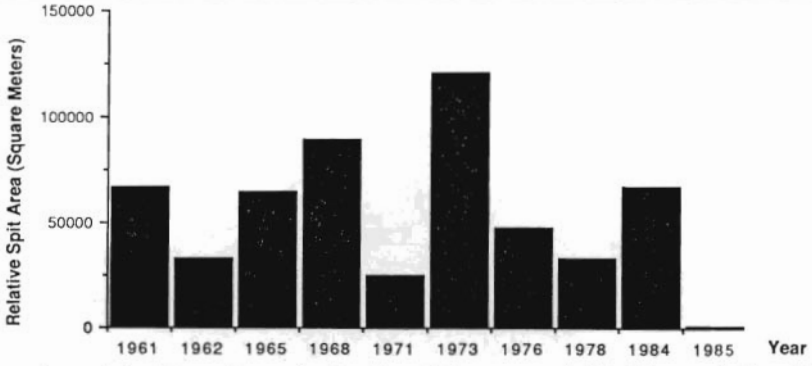


Figure 10. Semi-annual record of relative spit areas in Alsea Bay. Spit areas are calculated from available aerial photographs using the area between approximate low tide spit outlines to a reference line drawn due west of the base of Alsea Bay bridge. As of summer 1988 the relative spit area has remained near 50,000 m^2 following the 1985-87 period of spit accretion.

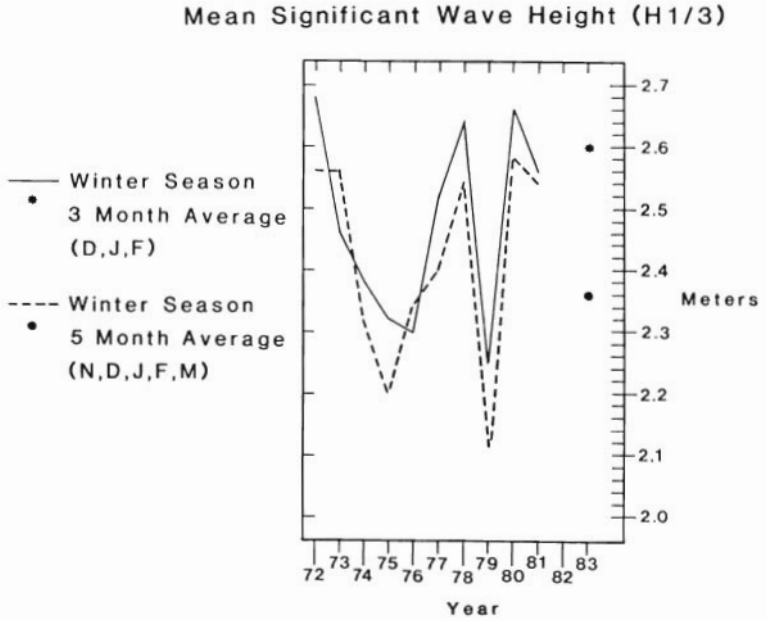
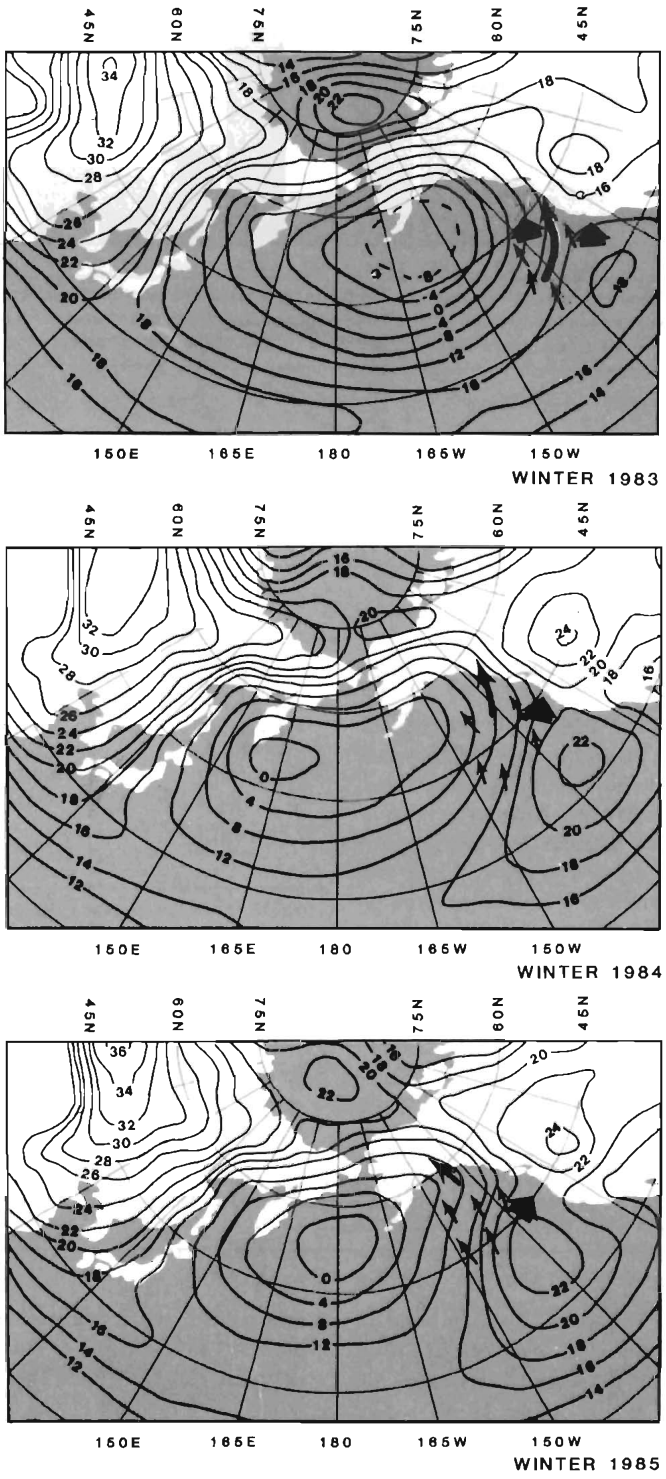
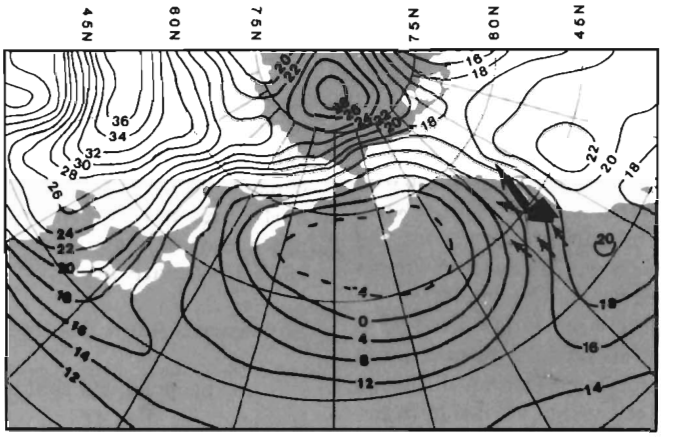


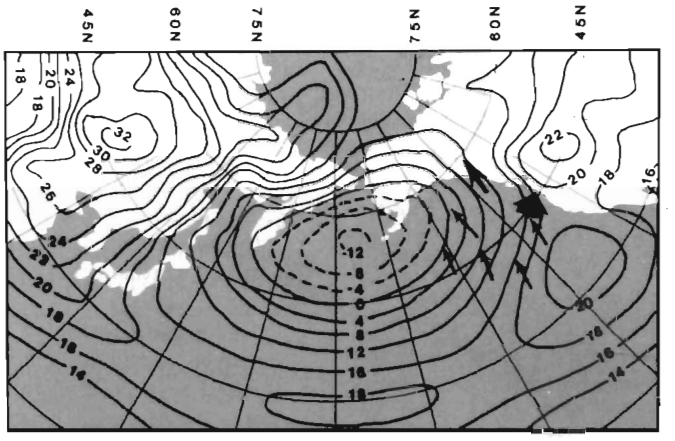
Figure 11. Annual plots of mean significant wave height ($H_{1/3}$) for the three month winter period Dec.-Feb. (solid line), and the five month winter period Nov.-Mar. (dotted line) for the years 1972-1981. Plots of seasonal $H_{1/3}$ Dec.-Feb. (asterisk) and Nov.-Mar. (solid circle) are also plotted for the winter of 1982-83. Mean significant wave height is estimated from the average of the one third largest waves recorded four times daily at Newport, Oregon.

unusual northward transport of beach sand in 1982-83. From the combined low pressure area and geostrophic wind direction inferences we would expect a surface wind stress 15-30° to the left of the geostrophic wind in the open ocean, and a total wind induced oceanic mass transport 90° to the right of the surface wind stress (Figure 12a-f). While the direction of winter wind-wave forcing is not directly aligned with the geostrophic wind, the direction of seasonal

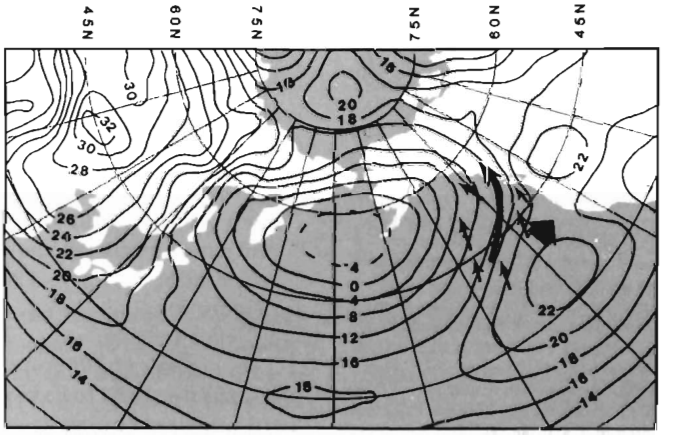

WINTER SEASON SEA SURFACE PRESSURE
1983-1988 (mb)
45N
60N
75N
75N
60N
45N
150E
165E
180
165W
150W
WINTER 1983
WINTER 1984
WINTER 1985



WINTER 1986



WINTER 1987



WINTER 1988

wind-wave forcing, relative to any point on the coast is clearly related to the latitude of the geostrophic wind guide.

Northward Sand Displacement

We have compared the relative trajectories of winter wind-wave forcing (1972-1988) using the central 1014-1016 mb geostrophic wind guide from the SLP charts as a proxy for the mean 'storm track' between the eastern Pacific low and high pressure areas. The landfall position of this geostrophic wind guide provides a means of comparing the latitude of maximum onshore wind-wave forcing between different winter seasons. The latitudinal variation in the 1014-1016 mb guide is used here only as a first order approximation to interseasonal wind-wave direction. The landfall latitudes of this storm track proxy are plotted for the years 1972-1988 (Figure 13) and they establish an anomalous southward shift of the 1982-83 maximum storm activity to a latitude of 35-40°N. The relations between the SLP storm track proxy and the mean wave direction have yet to be well constrained in the northeast Pacific. However, it is clear that a 10°-15° latitude southward deviation (1,000-1,500 km) of the SLP geostrophic wind guide from its mean latitude position (50°-55° N) can only indicate a greatly increased southernly component to the incident wave direction and ocean mass transport during the winter of 1982-83.

In order to substantiate the significance of the SLP storm track proxies in predicting the direction of seasonal wind-wave forcing, we have also plotted the 850 mb mean vector wind and the 850 mb vector wind anomaly for the winter of 1982-83 (Figure 14a, b). The vector wind anomalies confirm the indications of the SLP storm track proxies in establishing an anomalous southerly component of the onshore wind-wave forcing during the 1982-83 winter period. The low latitude of seasonal storm activity, relative to the study site of 44.4° latitude, resulted in a consistent southwesterly approach of winter surf. The unusually high angle of incident wave approach from the south would have consistently driven longshore currents to the north, producing the anomalous northward displacement of beach sand observed during the 1982-83 climatic event.

Southward Sand Displacement

It has been argued that southward longshore transport on the Oregon coast occurs primarily during summer periods when fairweather swells produced in high latitudes approach the shoreline from the northwest (KULM and BYRNE, 1966; KOMAR, *et al.*, 1976). Significant southward transport during the 1984-1985 summer periods should have been observed by (1) down cutting of the northern beach berms and (2) sand replenishment on the southern beach platforms. However, the first evidence of significant southward transport occurred during the winters of 1986 and 1987. The evidence for initial southward transport includes:

(1) The initial erosion of the anomalous beach berm and dune field south of the Seal Rocks Point, as constrained by aerial photographs of the dune field taken in 1985 (Figure 4) and 1986.
(2) The shallowing and southward growth of the truncated Alsea Bay spit, as established by monthly cross-sectional surveys of the inlet which showed significant shallowing starting in spring 1986 (JACKSON and ROSENFELD, 1987).
(3) The initial return of beach sand to the southern 7.4 km of the subcell during the spring of 1986, as observed by ourselves and shown in scaled photographs of selected beach sites taken in 1984, 1985 and 1986 (Figure 5).

The winters of 1986 and 1987 were the first winters after 1983 to have landfalls of the 1014-1016 mb storm guide proxy that plotted below 55° latitude (Figure 13). Not only were the fairweather swells of summer incapable of transporting sand to the south, but apparently the

Figure 12a,b,c (*Page 102*). Annual sea level pressure (SLP) charts of the north Pacific region for the three month winter period Dec.-Feb. for the years 1983-1988. The central 1014-1016 mb contour (geostrophic wind guide) is used to define the relative direction of maximum onshore wind-wave forcing, *i.e*, proxy for winter 'storm track.' Small black arrows indicate inferred wind stress. Medium arrows indicate geostrophic wind direction. Large arrows indicate oceanic mass transport.
Figure 12d,e,f (*Page 103*). Annual sea level pressure (SLP) charts of the north Pacific region for the three month winter period Dec.-Feb. for the years 1983-1988. The central 1014-1016 mb contour (geostrophic wind guide) is used to define the relative direction of maximum onshore wind-wave forcing, *i.e*, proxy for winter 'storm track.' Small black arrows indicate inferred wind stress. Medium arrows indicate geostrophic wind direction. Large arrows indicate oceanic mass transport.

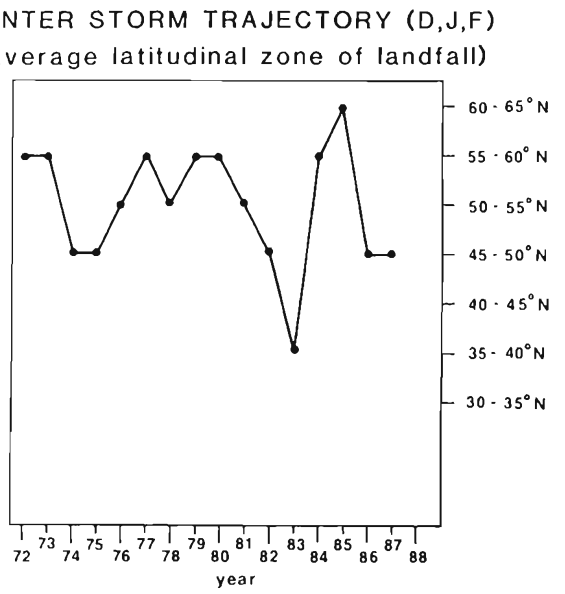


Figure 13. The relative latitude of winter 'storm track' landfalls are plotted for the years 1972-1987 based on the landfall position of the central 1014-1016 mb contour from the winter seasonal SLP charts in Figure 12.

winter storms of unusually high latitude during 1984 and 1985 were similarly ineffective in driving significant southward transport. The exceptional high latitude of the storm centers might also have resulted in decreased wave energy, due the displacement of the storm center from the central Oregon coast. It has yet to be established whether less than average wave energy was associated with the winter storm guide positions, estimated for the years 1984 and 1985. In conclusion, it appears to these authors that variable winter wave climates, and not winter-summer reversals of wave direction, were responsible for the longshore sand transport, both to the north and south, that was observed in the Seal Rocks subcell during the 1983-1988 study period.

Sea Level

Sea level is measured routinely from a tide gauge station at Newport, Oregon. Monthly mean sea levels from this station have been reported by PITTOCK *et al.* (1982) for the years 1967-1980, by HUYER *et al.* (1983) for the years 1982-83, and have been supplied to us by H. Pittock, Oregon State University, for the years 1983-1987. Winter seasonal averages (December-February) of mean sea level are plotted for the years 1972-1987, and they demonstrate that anomalous high mean seal levels (30 cm above average mean sea levels) occurred throughout the winter of 1982-83 (Figure 15). An unusual northward transport of seawater along the coast (Kelvin wave) and unusually low atmospheric pressure were associated with the 1982-83 ENSO event (HUYER *et al.*, 1983). Onshore oceanic mass transport from regional climatic forcing combined with the Kelvin wave and the low atmospheric pressure to produce the mean sea levels of exceptional height during this winter season (Figure 15). A coincidence of large storms with spring tide series possibly added to the effects of elevated mean sea levels in producing the extensive offshore (seaward) transport of beach sand during the 1982-83 winter (KOMAR, 1986).

The question arises as to whether the unusually high sea levels, and the associated seaward transport of sand, could have increased the anomalous northward sand displacement in 1982-83. For example, the offshore displacement of sand would have supplied an above average volume of sand to the surfzone during the winter months of northward littoral drift. It might not be possible, with the available data,

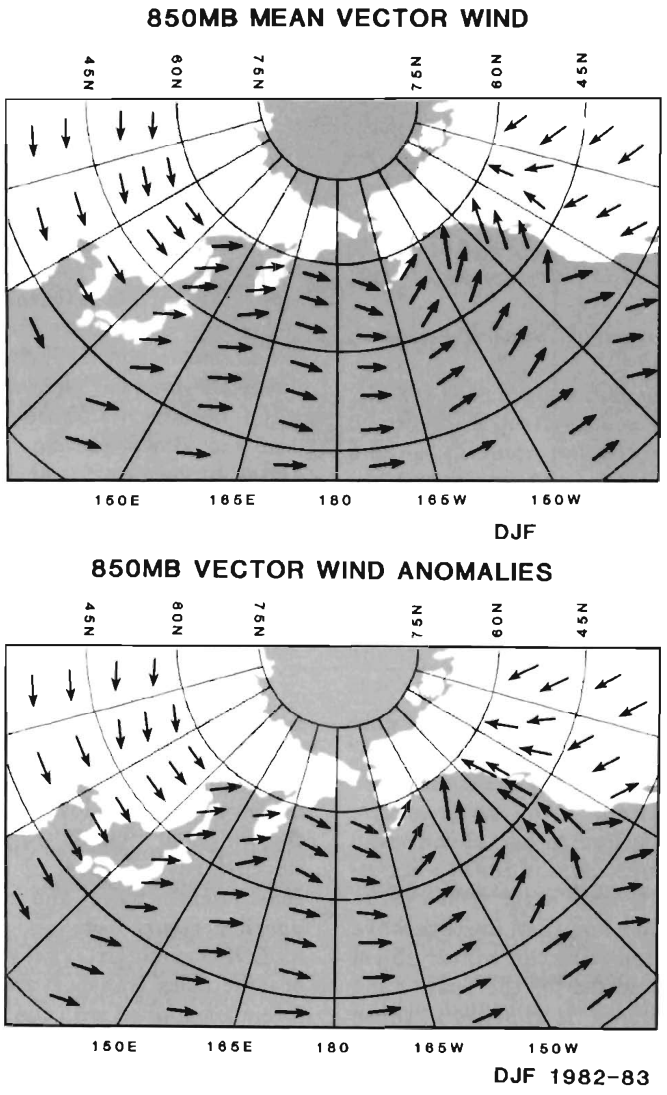


Figure 14a-b. 850 mb Mean vector wind and 850 vector wind anomalies are averaged and plotted for the months December, January and February of the 1982-83 winter season. The mean vector wind (a) shows the observed directional wind forcing (1982-83) while the vector wind anomaly (b) shows the difference between 1982-83 winter season of wind forcing and the mean directional wind forcing, using 1975-1979 as the representative base period (ARKIN, *et al.*, 1983).

to separate the longshore transport effects of (1) anomalous high sea level and (2) the exceptional southerly component of incident wave attack during the 1982-83 climatic event. However, the relative importance of anomalous mean sea level to the seasonal longshore transport within this cell might be evaluated by considering the southward return of beach sand after 1985.

It is clear that the southward return of beach sand, largely during the two years of 1986 and 1987, was not associated with exceptionally high values of mean sea level. For example, mean sea levels for these two years reached only 5-10 cm above the 15 year mean (Figure 15). Exceptional mean sea levels were not required for the subcell's apparent return to equilibrium conditions of longshore sand dis-

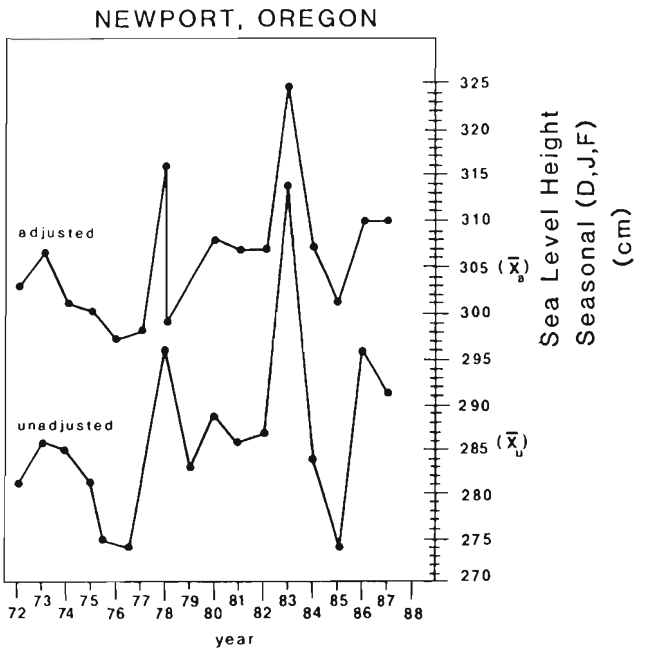


Figure 15. Mean sea level is averaged for the winter months (December, January and February) and the winter seasonal means are plotted for the years 1972-1987. Winter averages of adjusted mean sea level are also plotted for each year, and are based on 1 cm decrease of sea level for every one millibar increase in atmospheric pressure. The differences between unadjusted mean sea level and adjusted mean sea level indicate the influence of atmospheric pressure relative to water mass transport and thermal expansion in controlling mean sea level.

tribution after 1985. Ocean level set-up produced by major winter storms (DEAN, 1983) in 1986 and 1987 was apparently sufficient to bring the elevated beach berms and dunes in the northern part of the subcell to within reach of winter swash zones under the normal tidal range conditions of those two years. Mean sea level does not appear to be an important factor in the interannual longshore sand redistributions within this study area.

International Longshore Redistribution Versus Seasonal Exchange

Our best estimates of the 1982-83 sand displacement (4-6 $\times$ 10^2 m^3 per linear meter of shoreline) are based on differences between (1) conservative across-shore widths (200-300 m) of sand scouring to erosional platform surfaces (1983-85) and (2) profiles of fully accreted summer beaches (summer 1987). The potentially greater distances offshore to which surfzone sands were affected by the anomalous northward transport are not addressed in this study. In addition, the complete exposure of the beach platform south of profile F (Figure 6) indicates that sand supply was a limiting factor in the amount of sand displaced in this cell during the 1982-83 winter period.

By comparison, a seasonal onshore (summer)-to-offshore (winter) sand exchange volume of 110 m^3 per meter of shoreline was measured at a beach just north of Seal Rocks between 1973-74 (FOX and DAVIS, 1978). The 0.5 km long beach segment monitored by Fox and Davis is located about 6 km north of the Seal Rocks Point, and it roughly compares in beach width and slope to the beach between profiles F and I, north of Yachats Head. Even through the 1973-74 winter study period is characterized by moderate wave energy (Figure 10) and sea level (Figure 14) the seasonal across-shore sand exchange represents only 10-22% of the 1983-87 longshore sand redistribution, when normalized per unit length of shoreline.

Short-Term Sand Supply

An important question regarding the nature of beach sand budgets is whether or not onshore and offshore sand reservoirs are closely connected. The beach platform along most of the southern half of the Seal Rocks subcell remained largely uncovered for about two years after the initial sand displacement in 1982-83. During this two year period there was no significant resupply of sand to the beach from offshore deposits. The eventual return of sand to the southern onshore part of the subcell corresponded to diminishing onshore volumes of beach sand in the northern part of the subcell. The 1983-87 redistribution cycle of beach sand in the Seal Rocks subcell apparently occurred independently of potential offshore sinks or sources of sand. Interactions between the onshore and offshore sand reservoirs might occur over longer time scales than those associated with the brief interannual events of longshore sand redistribution that were observed during this study period. In contrast, longshore and shoreward (onshore) sinks of sand did play an important role in sand supply within some cells of the Pacific Northwest coast following the 1982-83 climatic event, as discussed below.

The impact of the 1982-83 sand displacement event is still being felt along some shorelines of the Pacific Northwest coast. For example, the northward displacement of beach sand resulted in the permanent loss of sand from at least three small littoral cells of central Oregon including Otter Rock, Hug Point and Netarts Bay (Figure 1). In the first two cells, a permanent loss of sand apparently occurred around the small headlands, Otter Rock (KOMAR, 1986) and Hugh Point. Some of the most extensive seacliff erosion (> 20 m) in recent history has occurred at Cove Beach, immediately south of Hug point, following the loss of sand from this small subcell in 1983 (unpublished data). In the Netarts Bay cell, sand was probably lost to a bay mouth and spit complex at the northern end of Netarts Bay (KOMAR, 1989). In all three cases, the lack of beach sand return during the last five years has resulted in ongoing erosion and local seacliff and/or shoreline retreat (10-20 m) in the southern end of these sand starved cells.

In contrast, the return of sand to the southern end of the Seal Rocks cell has precluded additional erosion of the low seacliffs there. Similarly the reported sea cliff erosion (1985) just north of Patricks Point (41.15°N) in northern California (TUTTLE, 1987) also largely ceased with the return of beach sand to the southern end of this cell in the spring of 1986. Clearly, the headland bounded segments of the Pacific Northwest coast responded differently to the 1982-83 sand displacement event on the basis of (1) available sand supply (2) effectiveness of bounding headlands and (3) presence of shoreward sand sinks.

Historic Record And El Niño Effects of Beach Erosion

While the 1982-83 displacement event was clearly exceptional within a several decade period (reports of long-term residents), the fact that other sand redistribution events have previously occurred in recent times is suggested by the cyclic erosion and accretion of the Alsea Bay spit (Figure 9). Earlier reports that the Alsea Bay spit had been gradually accreting to the south for the last couple of decades (STEMBRIDGE, 1975) are in error. At least four significant events of spit erosion and recovery have occurred within 24 years, resulting in an average recurrence interval of less than 10 years. It has yet to be established whether these smaller events of possible sand redistribution were synchronous coastwide and whether they were associated with accelerated sea cliff retreat.

The 1982-83 event of sand redistribution clearly coincided with a well documented El Niño-Southern Oscillation (ENSO) event (see Background). However, the earlier events of Alsea spit truncation in 1962, 1971 and 1978 (Figure 10) are not correlated with previous ENSO events reported by QUINN *et al.* (1987). Similarly, KOMAR (1986) did not find a strong correlation between the historical records of ENSO events and reported beach erosion in Oregon, with the possible exception of local erosion of the Siletz spit in 1972 and 1976 (El Niño years). Our study results suggest that it was the seasonal (winter) location of the north Pacific low pressure area (Aleutian low), and the resulting latitude of seasonal storm track (Figures 12-14) that largely controlled the

interannual directions of longshore transport and associated beach sand distributions during the 1982-1987 period.

Recent studies (NIEBAUER, 1988) have established a positive correlation between the intensity and position of the Aleutian low and El Niño-Southern Oscillation (ENSO) events. For example, the Aleutian low is intensified and eastward of normal in association with El Niño events. However, the Aleutian low is also reported to lack a preferred site during ENSO events (NIEBAUER, 1988), leading to the variable directional forcing of surface wind-waves associated with these climatic periods. It is clear that future efforts to establish any correspondence between interannual sand redistributions in littoral cells of the Pacific Northwest and ENSO events must take into account the relative position of the winter Aleutian low. Even so, such possible correlations will be difficult to identify due to (1) the brief and spotty historical record of coastal erosion in Oregon (KOMAR, 1986) and (2) the potential time lags (1-3 years) between climatic forcing events and associated shoreline response (seacliff erosion), as observed during this study.

CONCLUSIONS

An unusual northward displacement of beach sand in the Seal Rocks subcell was responsible for extensive sea cliff erosion and bay spit erosion observed in the southern half of the subcell between 1983 and 1985. An anomalously low latitude of storm activity during the 1982-83 winter period must have resulted in an exceptionally consistent approach of winter surf from the southwest. The anomalous high angle of seasonal wave attack together with seasonal wave energies that were slightly above average produced the northward displacement of beach sand.

The return of beach sand to the southern end of the subcell required a period of at least four years (1983-1987). No significant southward transport occurred from very-high latitude storm waves during the first two years (1984-85) after the initial displacement in 1982-83. Maximum interannual longshore transport between 1982 and 1987 was forced primarily by maximum winter storm paths with landfalls that were (1) sufficiently displaced from central trajectory latitudes to achieve consistent north or south angles of incident wave attack and (2) close enough to the central Oregon coast to produce high wave energy. Anomalously high values of mean sea level associated with the 1982-83 ENSO event possibly contributed to the extensive beach face erosion in 1982-83, but are not considered by us to have been important in the longshore displacement and recovery of beach sand during the 1983-1987 study period.

An average recurrence interval of less than ten years is estimated for four possible events of sand redistribution in the Seal Rocks subcell, as indicated by cyclic spit erosion and accretion at Alsea Bay over the last 24 years. However, historical aerial photographs and reports by long-term residents establish that the 1982-83 sand displacement event has been the most extensive in the last several decades.

ACKNOWLEDGEMENTS

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