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Aller au sommaire du numéro

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Résumé de l'article

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WAVE CLIMATE EFFECTS UPON CHANGING BARRIER ISLAND MORPHOLOGY, KOUCHIBOUGUAC BAY, NEW BRUNSWICK

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A quandary as to the role of storms in initiating barrier island morphological change in the Gulf of St. Lawrence has been posed by recent research. Although major changes are evident from historical documentation, none of the processes responsible has been witnessed since 1970. Detailed calculations of the nearshore wave power climate have been used in conjunction with historical evidence and short term profile measurements between 1970-1978 to resolve this problem in Kouchibouguac Bay, New Brunswick. Although the individual effects of seasonal storms are random along these barrier islands, the additive effects do reflect the overall nearshore wave climate. Greatest change has been wrought in those areas having highest wave power components normal and parallel to shore. If barrier segments susceptible to modification can be predicted for Kouchibouguac Bay, definition of nearshore wave climates could be used to determine such changes elsewhere in the Gulf.

INTRODUCTION

The barrier island systems of the southern Gulf of St. Lawrence have undergone substantial morphological modification over the past 150 years (Bryant and McCann 1973, Armon 1975, Reinson 1977). Most of this change can be accounted for by a recurring 20- to 50-year cycle of inlet-breaching and subsequent barrier accretion. These large scale, plan form changes may have been initiated by low frequency, high magnitude events. Such events and subsequent barrier alteration have not been recorded in the Gulf in the last eight years of research. Instead, higher frequency, lower magnitude events with a recurrence interval of a few months to several years may have been more important in modifying barrier morphology. This fact has been substantiated by recent research on the following: (1) nearshore processes and morphology in the Iles de la Madaleine (Owens 1975a,b, 1977) and Kouchibouguac Bay (Greenwood and Davidson-Arnott 1972, 1975); (2) frontal dune cliff retreat and landward migration of nearshore bottom contours (Kranck 1967, Bryant 1972, Armon 1975); (3) infilling of inlet breaches (Keyes 1975); (4) measured longshore growth and landward migration of barriers near inlets (Owens 1974a, Armon 1975, Reinson 1977, Munroe 1977); and (5) theoretical hindcasting of the Kouchibouguac Bay storm wave climate (Hale and Greenwood 1978). These higher frequency events are not to be confused with the regular and sequential passage of high and low pressure systems through the Gulf.

Preliminary attempts have been made at relating long term, gross, barrier morphological change to the overall wave climate generated within the Gulf (Bryant 1972, Armon and McCann 1977). In this paper, this relationship will be defined in more detail for the Kouchibouguac Bay barrier island system in New Brunswick. First, an offshore wave regime for Kouchibouguac Bay will be determined using deep-water wave periods, directions and heights reported for the southern Gulf. Second, the nearshore wave climate will be established using wave refraction, shoaling and bottom frictional attenuation theory for shallow water. Then relative variations in wave power normal and parallel to shore will be calculated near the breaker point for the various components making up this nearshore wave climate. Finally, correlations of longshore variation in wave power will be evaluated with: (1) longshore changes in barrier morphology over the last 150 years, and (2) measured dune cliff and ocean beach profile changes since 1970.

THE KOUCHIBOUGUAC BAY BARRIER ISLANDS

The Kouchibouguac barrier islands (Fig. 1) represent one of the better described shoreline segments of the southern Gulf of St. Lawrence

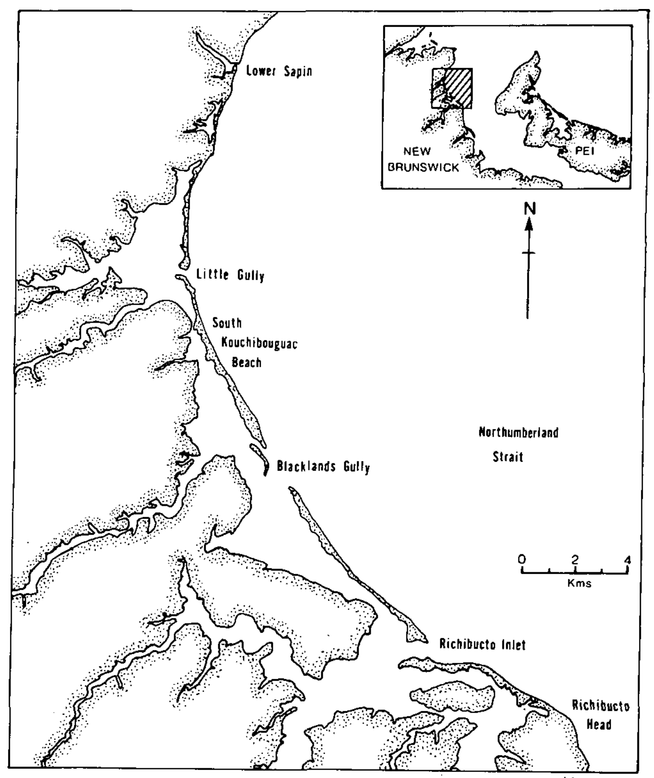

FIG. 1 Toponymic map of Kouchibouguac Bay.

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MARITIME SEDIMENTS Vol. 14, No. 2, August 1978 pp. 49-62

TABLE 1

Frequencies of waves by direction and height for Kouchibouguac Bay wave climate

DIRECTION	N	NNE	NE	ENE	E	ESE	SE	TOTAL
HEIGHT (m)								
0.0-1.0	8.7%	6.8	4.9	6.1	7.2	7.9	10.6	52.2%
1.0-2.0	6.4	5.3	4.1	5.1	6.2	1.3	3.6	32.0%
2.0+	4.9	3.5	3.1	2.4	1.9	---	---	15.8%
	20.0%	15.6%	12.1%	13.6%	15.3%	9.2%	14.2%	

(Kranck 1967, Bryant 1972, Davidson-Arnott 1971, 1975). The whole system overlies Pennyslvanian sandstones which, because of either cliff or off-shore bedrock erosion, have provided the source material for most barrier sands since the Holocene rise in sea level (Kranck 1972). The system is less complex than most in the Gulf mainly because of a restricted fetch window opening to the northeast. Barrier islands within the bay stretch in a 29-km long intermittent arc between Richibucto Head and Point Sapin. Three locationally stable inlets, Richibucto, Blacklands Gully and Little Gully, lie opposite the three main estuaries backing these islands.

The barriers occupy a low energy, micro-tidal environment (Davies 1964). The area has a mean tidal range of 0.67 m (Fisheries and Environment Canada, 1978) and a maximum predicted storm-surge range of 1 m. Predominant winds blow offshore from the west and southwest, and effective storm winds blow onshore from the northeast. Because of this pattern the bay is affected by wind-generated waves only 28.3% of the time; however, 37% of these waves are storm generated. The quiescent nature of the bay is further enhanced by the fact that maximum wind speeds tend to occur between the late fall and early spring, a period when the barriers are pre-eminently ice bound (Forward 1954).

Within this regime, accretional barrier forms in recent times have obtained a high degree of maturity and stability. Washover deposits make up less than 10% of the barrier length and are undergoing active dune accreation at present. Barrier widths (200 to 300 m) are comparable to other well-developed systems in the Gulf, and dune heights (4 to 8 m) are more than sufficient to prevent overwashing under most storm conditions. Lichen growth (*Cladonia cristatella* and *Cladonia rangiferina*) in dune areas is indicative of a long term dune stability approaching 50 or more years (McCann *et al* 1972).

Historically, a certain degree of sporadic instability characteristic of a higher energy wave regime has taken place (Bryant and McCann 1973). The most dramatic change, as evidenced from sequential map and air-photograph comparisons, has been the breaching and infilling around the three main inlets. This change has taken place conjunctively with adjacent barrier shoreline and offshore bar migration. Although barrier alteration around Richibucto Inlet can be related to the construction of breakwalls, plan form alterations around Blacklands Gully and Little Gully can be attributed only to the effects of waves. The apparent paradox in long- and short-term barrier stability can be resolved by invoking either a varying wave climate (that is higher magnitude events for the past) or localized, almost random, barrier responses to storm waves of a specific wave period and direction. Although these latter waves may have a random effect on the barrier during any one storm, on a cumulative basis, they may account for all historically recorded changes.

TABLE 2

Frequencies of waves by period and height for Kouchibouguac Bay wave climate (modified from Quon *et al* (1963)

PERIOD	4.0	5.0	6.0	7.0	8.0	9.0	10.0	TOTAL
HEIGHT (m)								
0.0-1.0	59.97%	2.59	2.03	0.33	0.13	0.07	0.08	65.20%
1.0-2.0	15.82	6.48	1.99	0.48	0.20	0.07	0.14	25.18%
2.0+	2.08	3.38	3.05	0.69	0.17	0.14	0.11	9.62
	77.87%	12.45%	7.07%	1.50%	0.50%	0.28%	0.33%	

TABLE 3

Frequencies of waves by direction, period and height for Kouchibouguac Bay wave climate (Table 1 & Table 2)

PERIOD DIRECTION & HEIGHT	4.0	5.0	6.0	7.0	8.0	9.0	10.0
N							
0.0-1.0	8.078%	0.349	0.274	---	---	---	---
1.0-2.0	4.168	1.707	0.524	---	---	---	---
2.0+	1.198	1.946	1.756	---	---	---	---
NNE							
0.0-1.0	6.255	0.270	0.212	0.034	0.014	0.007	0.008
1.0-2.0	3.330	1.364	0.419	0.101	0.042	0.015	0.029
2.0+	0.757	1.230	1.110	0.251	0.062	0.051	0.040
NE							
0.0-1.0	4.507	0.195	0.153	0.025	0.010	0.005	0.006
1.0-2.0	2.576	1.055	0.324	0.078	0.033	0.011	0.023
2.0+	0.670	1.089	0.983	0.222	0.055	0.045	0.035
ENE							
0.0-1.0	5.611	0.242	0.190	0.031	0.012	0.007	0.007
1.0-2.0	3.204	1.312	0.403	0.097	0.041	0.014	0.028
2.0+	0.519	0.843	0.761	0.172	0.042	0.035	0.027
E							
0.0-1.0	7.413	0.327	0.257	0.042	0.016	---	---
1.0-2.0	4.485	1.837	0.564	0.136	0.057	---	---
2.0+	---	---	---	0.132	0.034	---	---
ESE							
0.0-1.0	7.325	0.317	0.248	---	---	---	---
1.0-2.0	0.847	0.347	0.107	---	---	---	---
2.0+	---	---	---	---	---	---	---
SE							
0.0-1.0	9.842	0.425	0.333	---	---	---	---
1.0-2.0	2.345	0.960	0.295	---	---	---	---
2.0+	---	---	---	---	---	---	---

DEEP WATER WAVE CLIMATE

An offshore wave climate for Kouchibouguac Bay was built using existing hindcast and observational data for the southern Gulf (Quon *et al* 1963, Ploeg 1971, Atmospheric Environment Service data quoted in Armon and McCann 1977). This wave climate includes frequencies by wave direction, period and height. Wave frequencies by height for northerly to easterly directions were calculated from data obtained by the Atmospheric Environment Service from ship observations between 1963 and 1971 in the Gulf. Frequencies by height for east-southeasterly and southeasterly directions in Northumberland Strait were hindcasted using wind speed data measured at Summerside Airport (Canadian Department of Transport 1968) and a fetch-limited nomogram developed by Bretschneider (United States Army Coastal Engineering Research Center 1977). These frequencies are summarized in Table 1. Northerly waves predominate in Kouchibouguac Bay, and waves with heights between 0.0 to 1.0 m prevail for about 50% of the time.

The only comprehensive study of wave period frequencies in the southern Gulf was undertaken by Quon *et al* (1963) for the period 1956-1960 (Table 2). The data were calculated using hindcasting procedures and lack directional resolution. Sixty percent of the hindcasted waves have a wave height of less than 1.0 m and a mean period of 4 seconds. Four-second period waves, all totalled, account for 77.87% of all waves and 5.0- and 6.0-second period waves account for 12.45% and 7.07% respectively of the total. Davidson-Arnott (1975) in the summer of 1973 measured nearshore wave frequencies within Kouchibouguac Bay which were similar to these latter frequencies (5.0 sec, 10% frequency, 6.0 sec, 5%). Hindcasted wave heights exceeding 2.0 m are relatively scarce (9.62% frequency) and waves with periods greater than 7.0 seconds are infrequent (2.6% frequency).

An overall wave climate, characteristic of Kouchibouguac Bay rather than the southern Gulf, was obtained by combining Tables 1 and 2. This wave climate (Table 3) accounts for both waves found in the southern Gulf of St. Lawrence and local wind waves generated in Northumberland Strait. Because of either land mass or refraction effects, waves

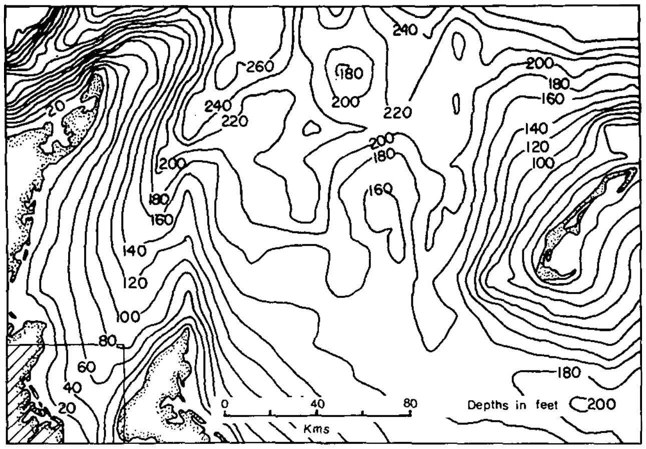

FIG. 2a Bathymetric map for the southern Gulf of St. Lawrence.

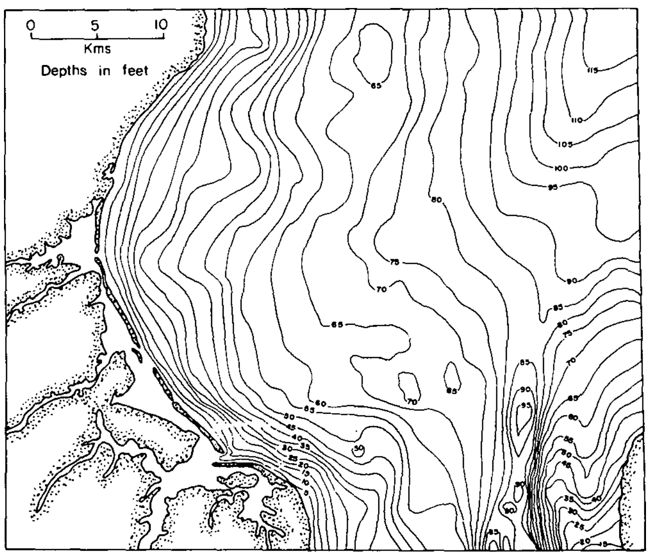

FIG. 2b Bathymetric map for Kouchibouguac Bay.

with periods greater than 7.0 second from the north, east-southeast and southeast, and waves with periods greater than 9.0 seconds from the east have been excluded from the data. Also because of fetch restrictions within Northumberland Strait, wave heights greater than 2.0 m from the east-southeast and southeast have been ignored. The most common waves in Kouchibouguac Bay are those from the southeast and north with a 4-second period and height of less than 1.0 m. Unfortunately, as will be shown, these waves do not affect all parts of Kouchibouguac Bay because of wave refraction shadow effects.

DESCRIPTION OF COMPUTER WAVE REFRACTION PROGRAM

The deep-waver wave climate presented in Table 3 is not representative of nearshore wave conditions along the Kouchibouguac barrier islands. Waves with a period greater than 6.0 seconds are strongly fr cted over ontinental-sh f b t ym y southern Gulf, and waves with periods less than 6.0 seconds undergo substantial modification within Kouchibouguac Bay. At present, the most efficient method for delineating wave refraction, shoaling and bottom frictional attentuation effects over inshore bathymetry is by means of computer simulation. A program, written by Dobson (1967) and modified for frictional attenuation of wave energy by Coleman and Wright (1971), was used for this purpose. In the Dobson program, a second degree polynomial is fitted to regularly gridded bathymetry using a least squares algorithm. Calculations in the program are based upon progressive, linear, gravity wave theory which can be used assuming small wave steepness, constant water depth and a wave period that is a constant unique function of wave celerity and length. In addition, it is assumed that wave diffraction and reflection are non-existent, that waves are monochromatic, that wave energy is conserved laterally along the wave crest, that refraction is independent of wave height and that water percolation, bed disturbance and current effects are insignificant. The assum tion of monochromatic waves is very tenuous given the lower period, "sea" state wave characteristic of the southern Gulf. While the other assumptions also can be challenged (diffraction: Worthington and Herbich, 1970, dependency on wave height: Chu 1975 and Hebenstreit 1977, bed permeability: Hunt 1959 and Liu 1977, bed disturbance: Tunstall and Inman 1975 and Suhayda 1977, currents: Longuet-Higgins and Stewart 1960 and Johnson 1974), the greatest flaw in the program lies in the use of linear wave theory. Such theory is not applicable inside the breaker zone (Wood 1970, Chandler and Sorenson 1972) and not totally appropriate in characterizing waves in nearshore and offshore areas (Wood 1969, Iwagaki and Sakai 1970, Whalin 1972). These limitations must be realized when applying the Dobson program to real-world situations.

The basic Dobson program requires only four parameters as input: (1) a controlled offshore a yme ric gri , (2) wave period, ( ) heigh an (4) direction. Wave input consisted of each viable combination of wave direction, period and height given in Table 3. Two bathymetric grids were used. The first grid (Fig. 2a) consists of offshore depths for the southern Gulf of St. Lawrence (Canadian Hydrographic Chart No. 4002, 1964 ed.). Bathymetry for this grid is characterized by a trough leading into Northumberland Strait. Waves with periods greater than 6.0 seconds were positioned in deep water on this grid (orthogonal spacing less than 3.77 km) and then corrected shorewards for refraction, shoaling and frictional attenuation effects on the shelf until the boundary of the second, more detailed, grid of Kouchibouguac Bay was reached (bathymetry based on Kranck 1967). Bathymetry for the second grid is characterized by a deep trough cutting into the middle of Northumberland Strait and by three shoals projecting seawards from Richibucto Head, South Kouchibouguac Beach and Lower Sapin (Fig. 2b). Both refracted waves from the Gulf and smaller period waves generated within the limited fetch of Northumberland Strait were passed across this latter grid at orthogonal spacings of less than 670 m. In some cases, areas of crossed orthogonals, caustics, were generated over inshore shoals. Because wave heights in areas of caustics cannot be approximated by linear wave theory, the simulated wave data were checked for extreme refraction effects and then were excluded if refraction coefficients exceeded either 10.0 in offshore waters or 2.0 at the breaker point (limits based upon Mogel *et al* 1970). Breaker wave characteristics were calculated along the remaining orthogonals when either waves broke (water depth to wave height ratio was less than 1.28, Miche 1944) or waves were less than 670 m from shore.

Nearshore wave characteristics were calculated for 1596 orthogonals representing 96 combinations of wave direction, period and height. The barrier length between Richibucto Head and Lower Sapin was segmented into 64 units, each 0.5 km in length. Data on each orthogonal were references as a linear distance from Richibucto Head and used to characterize wave parameters for these various units of coastline. Each wave parameter then was weighted according to its frequency of occurrence (Table 3). If the shoreline spacing between wave orthogonals for a specific wave direction, period and height was greater than 5 km, data were excluded from subsequent analysis for the intervening segment of coast. The resulting data matrix could be manipulated to give a mean value for any nearshore wave characteristic for: (1) any specific wave direction, period or height, (2) any combination of these three wave parameters, or (3) the total wave spectrum. This could be done for: (1) any 0.5-km segment of coastline, (2) any length along the barrier, or (3) the barrier island system as a whole.

RESULTS OF WAVE REFRACTION

(a) General

As a general summation of nearshore wave characteristics in the bay, refraction diagrams for 6.0-second waves are presented in Figure 3 for all directions. Refraction of orthogonals tends to be more severe for higher wave periods and less severe for lower periods. The barrier islands north of Richibucto Inlet and south of Little Gully are sheltered from northerly and southeasterly waves respectively. These results are in agreement with field observations under these wave conditions. The barrier island plan form is adjusted best to east-northeast waves. Waves from other directions tend to be concentrated on the barriers north of Richibucto Inlet, adjacent to Blacklands Gully or north of Little Gully. Divergence of wave rays occurs most frequently near the three inlet mouths. These refraction patterns are strongly dependent upon the location of shoal protuberances along the barriers.

Wave power components normal and parallel to shore were used to characterize the nearshore wave regime of the barriers. (All wave parameters used in this study are defined mathematically in Table 4). The shoreward component of wave power is an important parameter for defining onshore-offshore sediment transport rates to the beach foreshore, swash uprush limits, and locations susceptible to overwashing and dune cliff erosion. Mathematically, wave power normal to shore is a function of wave height, which in turn depends upon refraction, shoaling and frictional attenuation coefficients. These latter two co-efficients are depth dependent. The longshore component of wave power is an important parameter for defining longshore sediment-transport vectors. The rate and direction of sediment movement determines the speed at which inlets infill, and beaches either erode or accrete. Longshore wave power is a function of wave power and the angle of wave incidence expressed as a sine-cosine function.

TABLE 4

Mathematical definition of wave power terms used in study

Pn	$= P(1-\sin\alpha\cos\alpha)$
Pl	$= P\sin\alpha\cos\alpha$
P	$= CgE/CT$
E	$= \rho g Hb^2 L/8$
Hb	$= KrKsKfHo$
Kr	$= \lvert B\rvert^{\frac{1}{2}}$
Ks	$= (Co/Cg)^{\frac{1}{2}}$
Kf	$= Hf_j/(KrKsHo)$
Hf_j	$= \dfrac{Hf_{j-1}}{((f\phi\Delta x Hf_{j-1})/Ks_j T^4)+1.0}$
Hf_{j-1}	$= Hf_{j-1}(Ks_j/Ks_{j-1})\ (Kr_j/Kr_{j-1})$
ϕ	$= (\rho\pi^3/3g^2)\ (Ks_j/\sinh 2\pi d/L)^3$
T	= wave period
Co	= deep water wave velocity
Ho	= deep water wave height
L	= wave length
C	= wave velocity
Cg	= wave group velocity
E	= wave energy
P	= wave power
Pn	= component of P directed shorewards
Pl	= component of P directed alongshore
Hb	= breaker wave height
Hf_j	= wave height after frictional attentuation at location j on orthogonal
Δx	= distance of Hf_j from Hf_{j-1} on orthogonal
d	= water depth
f	= bottom friction coefficient (.02)
g	= acceleration due to gravity
ρ	= water density
Kr	= refraction coefficient
Ks	= shoaling coefficient
Kf	= friction attenuation coefficient
$\lvert B\rvert$	= wave orthogonal separation factor
α	= wave angle to bottom contour

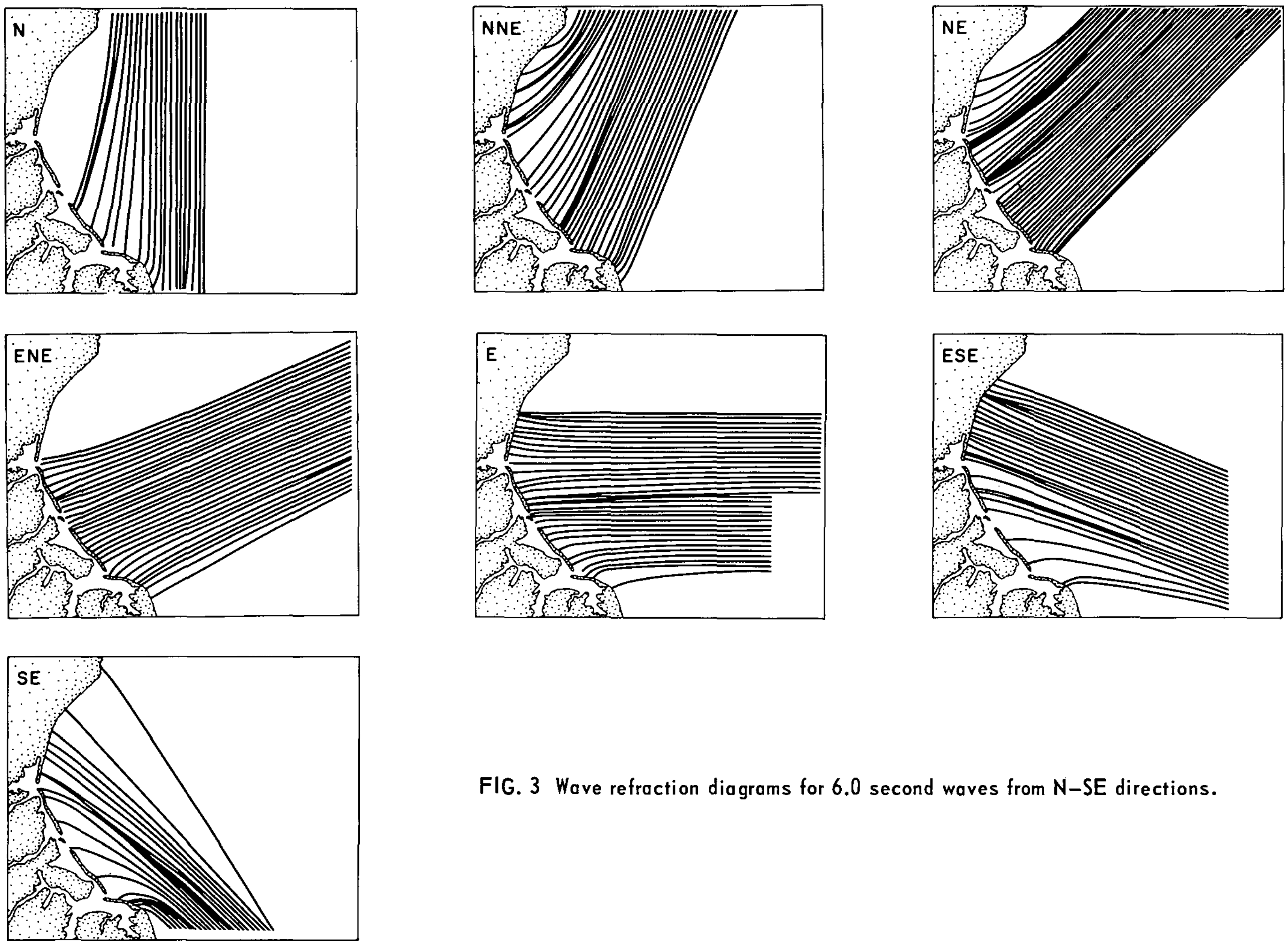

FIG. 3 Wave refraction diagrams for 6.0 second waves from N–SE directions.

Because of the procedures used to locate nearshore data points in the study, longshore variation in wave characteristics may be a function of a longshore variation in nearshore slope rather than offshore modification of incoming waves. To investigate this possibility, the relative linear dependence of normal and longshore wave power components upon breaker wave height, water depth, angle of wave incidence, and the refraction, shoaling and frictional attenuation was examined further using stepwise regression analysis (Nie *et al* 1975). The results of these analyses are presented in Table 5. Seventy-nine percent of the variation in the normal component of wave power can be explained solely by breaker wave height. Only 1.5% is explained by water depth and 1.7% by the other co-efficients. The results are similar for longshore wave power with 47.8% of the variation in longshore wave power being explained by breaker wave height, 16.6% by the angle of wave incidence, 1.5% by water depth and 1.0% by the other terms. The dependence of wave height upon water depth and the variation of water depth with distance from Richibucto Head also were evaluated. Water depth accounts for less than 1.2% of the variation in wave height and varies randomly with distance along the barrier islands. Implied in these results is the fact that longshore variation in the nearshore wave power terms in this study reflect nearshore modification of the wave climate rather than any systematic change in nearshore slope along the barriers.

(b) Summary of Wave Power Parameters

Summaries of the wave power terms for various wave components of the wave spectrum are presented in Table 6. Overall, wave power near the breaker point averages 560.9 gmcal/m/sec. Of this total, 76.6% is directed shorewards and 25.4% is directed alongshore. Only 15% of wave power is lost by frictional attenuation of waves passing over the shelf. The longshore wave power component can be subdivided further into southward and northward components. A residual directional component then can be computed for use in longshore sediment transport calculations. This residual can be determined by taking a mean grain size value of 0.33 mm for nearshore sediment in Kouchibouguac Bay (Greenwood and Davidson-Arnott 1972) and using the following formula relating grain size to the bottom orbital velocity required for threshold movement of sediment (Komar and Miller 1973):

TABLE 5

Linear dependency of wave power components normal to, and parallel with shore to various nearshore parameters

	Wave power normal to shore	Wave power parallel with shore
Wave height	79.0%	47.8%
Water depth	1.5%	1.5%
Angle wave incidence	--	16.6%
Refraction coefficient	0.3%	*
Shoaling coefficient	1.4%	0.8%
Friction coefficient	*	0.2%

* no significant change to degree of correlation when added to the stepwise regression equation

$$D = \pi\left(\frac{P}{(Ps-P)\ g\ 0.21}\right)^2 \frac{Um^3}{T}$$

D = maximum sediment size entrained
P = density of water
Ps = density of particle
g = acceleration due to gravity
Um = maximum bottom wave orbital velocity
T = wave period

A northward residual wave power value of 23.7 gmcal/m/sec was calculated for the total wave climate using this procedure. This theoretical value is in contradiction with morphologically determined evidence indicating southward longshore movement of sediment (Bryant and McCann 1973, Owens 1974b).

The highest wave power value (853.7 gmcal/m/sec) and highest onshore component (691 gmcal/m/sec) both occur with northeast waves; however, the greatest relative onshore component exists with east-northeast waves (18.5%). Because beach plan form adjustment is greatest where longshore transport potential is least (Davies 1960), the Kouchibouguac barrier plan form must be adjusted best to east-northeast waves. Waves from the east to southeast have northward components of longshore wave power, and waves from the north to northeast have southward components. The fact that 42.8% of wave power for southeast waves is directed longshore may indicate that these waves are not as common as implied in Table 3. If they were, then the barrier island plan form would be better adjusted to waves from this direction.

Greatest wave power values are generated by 6.0 - and 5.0-second period waves (948.6 and 860.4 gmcal/m/sec respectively). Wave power values decrease sharply for 4.0-second waves (438.9 gmcal/m/sec), but the greatest reduction occurs as wave period increases (382.2 gmcal/m/sec for 10-second period waves). This latter trend is related directly to the increased divergent refraction of higher period waves into the bay. Longshore wave power values do not vary as much with wave period as with wave direction. Large period waves (>7.0 sec) have smaller components of longshore wave power)12.9 to 15.8%) than lower period waves (19.5 to 29.2%). This result implies a better adjustment of barrier plan form to higher period waves as well as to ENE waves, - a result supported by Davies (1960) for beach plan orientation in a swell environment and by Bryant (1977) for equilibrium establishment of sediment transport along beach foreshores. Because larger period waves have southerly residual longshore components of wave power, they may account for the southward movement of sediment interpreted from morphological evidence and thus be more frequent than implied in Table 3.

RELATIONSHIPS BETWEEN BARRIER MORPHOLOGICAL CHANGE AND WAVE POWER PARAMETERS

(a) Long Term

The average longshore variation in the two wave power components and in the residual direction of longshore wave power for the total wave spectrum between Richibucto Head and Lower Sapin is plotted in Figure 4. Areas of ephemeral washover, major inlet breaches and infilling are superimposed on these trends. Points have also been marked where one wave of a specific direction or period accounts for most of the wave power along the shore.

Of note in Figure 4 is the fact that onshore wave power components are lowest immediately opposite the three major and permanent inlets of the system. These low values result from divergent wave refraction over relict fluvial channels drowned with the Holocene rise in sea level (Kranck 1972). The association between areas of low wave power and inlet

TABLE 6
Summary of Wave Power Components for Wave Direction, Period, Height
In Kouchibouguac Bay Nearshore Zone - Averages (gmcal/m/sec)

DIRECTION							
	N	NNE	NE	ENE	E	ESE	SE
P	441.5	560.9	853.9	751.4	598.0	196.5	216.0
Pn	299.6	409.6	691.0	612.5	410.6	131.9	123.5
Pl	141.9	151.3	162.9	138.9	187.4	64.6	92.5
Pl_{res}	9.5S	81.2S	33.7S	44.1N	162.7N	41.5N	53.9N
%Pl/P	32.2	27.0	19.1	18.5	31.3	32.9	42.8
PERIOD							
	4.0	5.0	6.0	7.0	8.0	9.0	10.0
P	438.9	860.4	948.6	695.3	590.9	520.3	382.3
Pn	310.9	668.8	763.6	600.0	497.5	453.4	331.9
Pl	128.0	191.6	185.0	95.3	93.4	66.9	50.4
Pl_{res}	31.1N	26.2N	29.8S	18.0S	47.6S	20.0S	25.1S
%Pl/P	29.2	22.3	19.5	13.7	15.8	12.9	13.2
HEIGHT							
	0.0-1.0		1.0-2.0		+2.0		
P	124.0		893.6		1324.8		
Pn	86.8		650.8		1048.6		
Pl	37.2		242.8		276.2		
Pl_{res}	12.2N		77.1N		57.7S		
%Pl/P	30.0		27.2		20.8		
TOTAL SPECTRUM							
P	560.9						
Pn	418.4						
Pl	142.5						
Pl_{res}	23.7N (18.2N if N & SE waves ignored)						
%Pl/P	25.4						

position is in accord with Bascom's (1954) basic premise that inlets coexist with positions of lowest wave energy. More significantly, highest wave power values exist adjacent to these inlets. Most of this wave power can be accounted for by convergent refraction of northeast or east-northeast waves, having periods of 5.0-6.0 seconds, over either shoal projections adjacent to each inlet or weakly developed ebb tidal deltas. Davidson-Arnott (1975) considers these waves to be the dominant storm waves of Kouchibouguac Bay.

This theoretical longshore wave power variation substantially accounts for barrier island change over the past 150 years. Stable inlet channels occupy positions with the lowest onshore component of wave power, and areas of historical major inlet breaching, especially around Blacklands Gully, occupy positions with higher wave power. Inlet breaching east of Richibucto Inlet is exceptional, but here barrier modification has resulted directly from construction of a breakwall on the north side of the inlet (Bryant 1972). Most areas of present washover and substantial lagoon infilling, some of which has no direct correspondence to known inlet or washover positions, also lie concomitantly with areas of higher wave power. Except for a small area 3 km north of Richibucto Inlet, these areas are adjacent to beach sections where average wave power components normal to shore exceed 450 gmcal/m/sec.

Variation in the longshore component of wave power along the bay shore is indicative of changes in barrier form due to longshore sediment movement. Longshore wave power values are highest to the east of Richibucto Inlet, on both sides of Blacklands Gully and north of Little Gully. These areas coincidently have substantial offshore shoals. Except for the extreme north end of the bay and the Richibucto Inlet area, residual longshore wave power values, averaged for the whole wave spectrum, are quite low. The Kouchibouguac barrier system is one with a passive longshore transport regime.

Despite this passive response, the residual southward and northward components of longshore

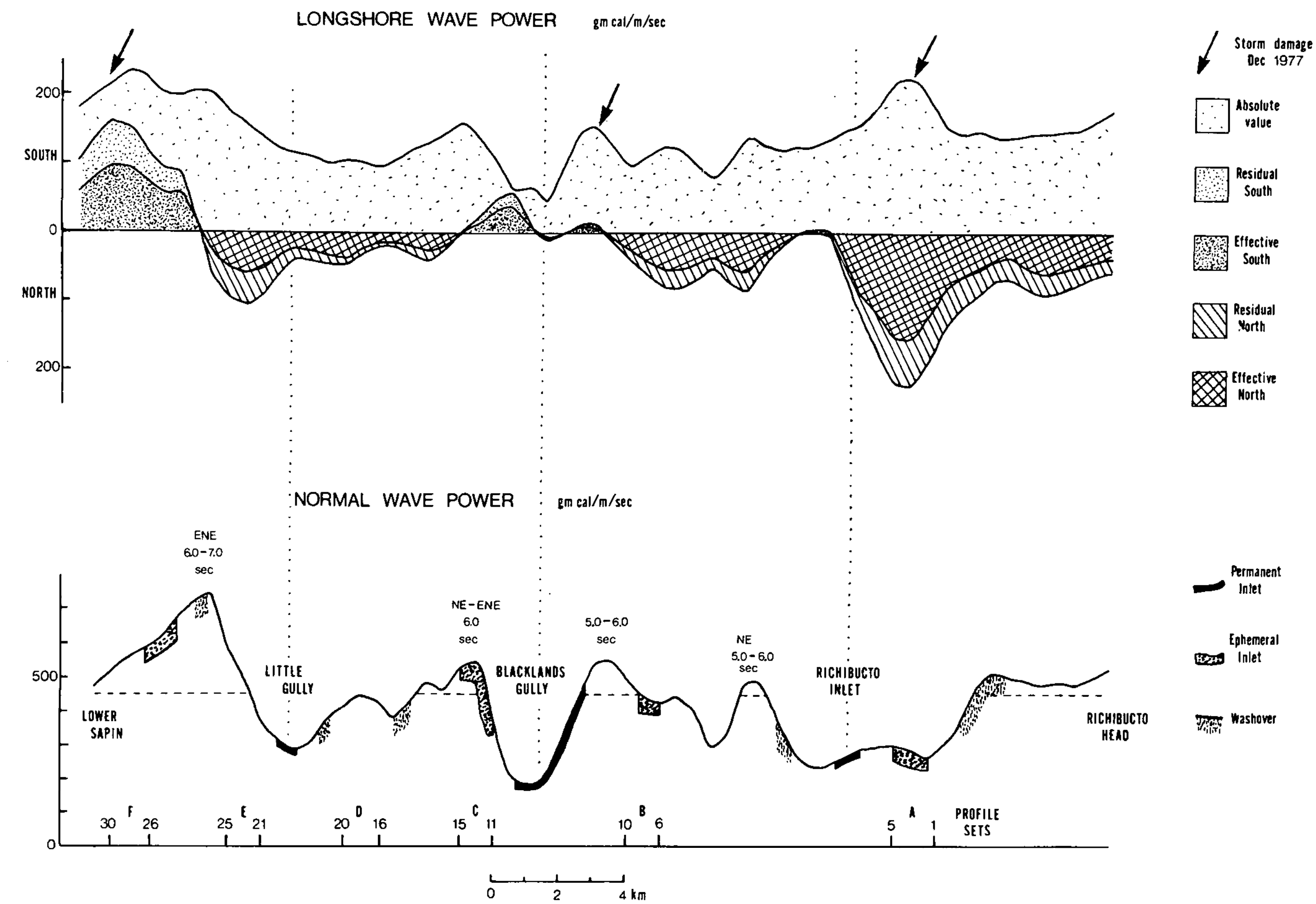

FIG. 4 Variation in longshore and normal components of wave power between Richibucto Head and Lower Sapin averaged for whole wave spectrum.

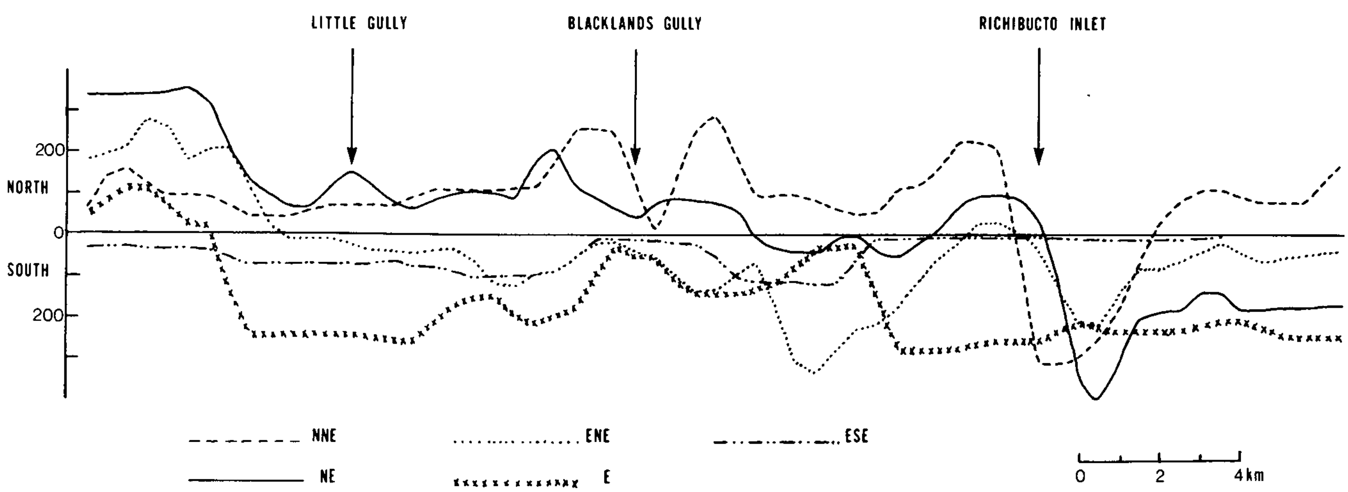

FIG. 5 Variation in the directional residual component of longshore wave power for NNE–ESE wave directions between Richibucto Head and Lower Sapin (gmcal/m/sec).

wave power are important in determining sediment transport vectors and barrier evolution. If maximum longshore wave power values are high, but resultant southward or northward components are small, then minimum changes in barrier plan form are to be expected along unbroken sections of the coast. Here the same nearshore sediment is just being moved back and forth alongshore. However, if inlets are present then rapid infilling can be expected because large volumes of sediment are being moved alongshore from both directions. Such a situation occurs on both sides of Blacklands Gully. Here, absolute longshore wave power values are high but residual values are very low. This barrier segment historically has been the location of a major sediment sink. Flood tidal deltas and overwash lobes have intruded to their maximum extent onto the lagoon backing Blacklands Gully.

Residual longshore wave power values tend to increase north and south from Blacklands Gully. Maximum southward components are found at the north end of the barrier system concomitantly with maximum longshore wave power values. This result is supported by morphological evidence in the way of offshore shoal and inlet deflection southwards. Maximum northward components are found east of Richibucto Inlet; however shoals around Richibucto Inlet are not deflected northwards, but southward (Kranck 1967, McCann and Bryant 1973). This contradiction most likely is due to the fact that offshore shoal bathymetry here was not described adequately in the computer refraction program.

This latter explanation cannot be invoked to explain the difference between theoretically predicted and observed sediment movement averaged over the bay. In order to clarify this contradiction, longshore variations in the residual components of longshore wave power were examined for each wave direction (Fig. 5). There is considerable variation in residual wave power vectors with changing wave orientation. Northward components of longshore wave power in the bay are linked exclusively to waves from the east-northeast, east or east-southeast and southward components are associated with waves from the north-northeast or northeast. Because waves from these latter directions have southward residual longshore wave power vectors, then they may occur more frequently than indicated in Table 3. Because storm waves in Kouchibouguac Bay also originated from northeast, storms may be responsible for generating much of the observed longshore changes in barrier form.

(b) Short Term (1970–1978)

Short term changes in barrier plan form were examined using 6 sets of 5 profiles along the front of the barrier island chain (locations outlined in Figure 6). Sets B, C, E and F were first established in the late spring of 1970 while sets A and D were established in the spring of 1972. An attempt was made to resurvey all profiles in December 1977 and May 1978. The earlier survey was interrupted on December 7th by a major storm that was accompanied by a storm surge in excess of 1.0 m. During this storm, dunes fronting a barachois at the extreme north end of the study area were completely destroyed by overwashing, while a fresh inlet was breached 300 m south of Little Gully.

Ten out of 15 profile benchmarks in sets B, C and D were relocated both before and after the storm; however, only 2 of the 15 benchmarks in sets A, E and F were found in May 1978. Only 1 of the 5 benchmarks in the extreme northern section of the bay was found in May 1978. The others were most likely obliterated during the December storm. Benchmarks in the southern sets, south of Blacklands Gully and Richibucto Inlet, probably disappeared with either slow dune erosion or storm activity since 1973. These latter areas are locations where continuous frontal dune cliffing has occurred between 1970-1978.

The net profile changes between 1970 and December 1977, and between December 1977 and May 1978 are outlined, where possible, in Figure 6. Except for one profile (No. 24 north of Little Gully), the ocean beach foreshore profile has maintained an equilibrium location over the past 8 years. Most profile changes have occurred at the dune cliff. Except for profile 12, just north of Blacklands Gully, dune fronts prograded between 1970 and December 1977. Dune truncation on all profiles was instigated by the December 1977 storm. The resulting erosion was two to three times greater than the accretion which occurred over the previous 6 to 8 years. This change was by no means consistent along the barrier. On profile 8, situated south of Blacklands Gully, dune accretion since 1970 was greater than erosion during the December storm; however 400 m north of this profile, erosion was so severe that the barrier was almost breached by wave overwashing. On profile 26, situated at the north of Kouchibouguac Cay, sand actually accreted during the period 1972 to 1978, despite the effects of the December storm; however 0.5 km northwards, the dune ridge, which extended 2 to 4 m above the low tide level, was destroyed completely. On two profiles north and south of Little Gully (profiles 19 and 21), the erosion which occurred during the December storm was not exceptional; however within the intervening distance, a minor inlet was forced through the barrier.

For the 8-year period, average rates of erosion or accretion in the 6 sets of profiles could not be related to any variations in wave power normal to shore. Some areas of erosion could be correlated with areas of higher longshore wave power values. The erosion which occurred at the north end of the barrier chain and south of Richibucto Inlet was situated in areas having the highest average longshore wave power values. The fact that the beach foreshore profile in the centre of the bay did not vary significantly over the 6 to 8 year period may be indicative of low residual longshore wave power values. The fact that changes over the short term correlate partially with increased longshore wave power values may reflect the adjustment of the barrier plan form and morphology to periodic storms occurring every few years. The December storm fits this pattern as it has a recurrence interval of only 12 years (Hale and Greenwood 1978). The changes in barrier morphology wrought by this storm however were spatially random. Such irregular changes may reflect the unique nearshore wave climate of deeper-water waves of a specific direction and period. Over the long term these uniquely

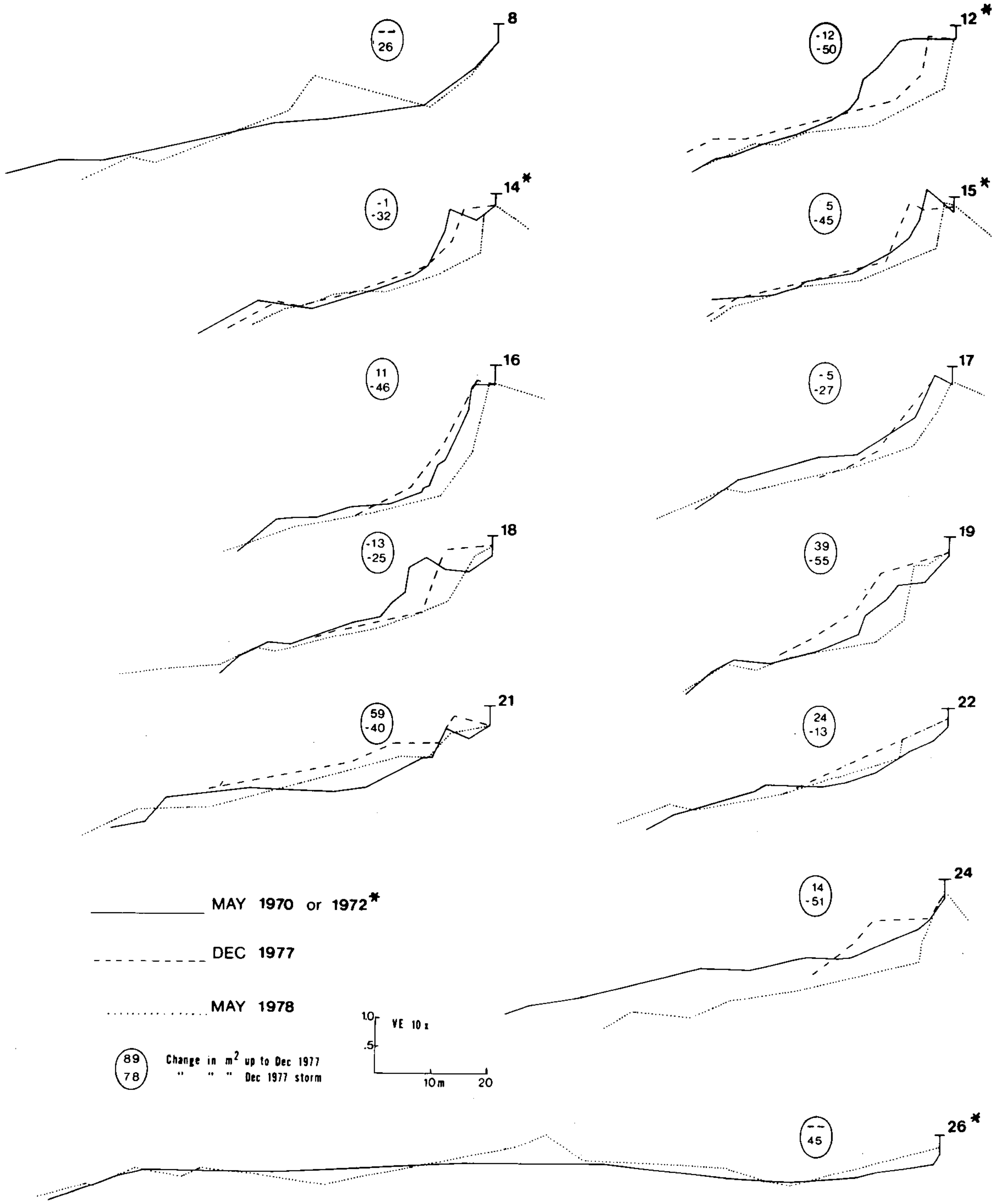

FIG. 6 Selective profile changes on the ocean beaches of Kouchibouguac Bay between May 1970 and May 1978.

defined trends may be averaged out such that gross barrier changes are responding more accurately to the overall nearshore wave climate.

CONCLUSIONS

The barrier islands of the southern Gulf of St. Lawrence have undergone active modification over the past 150 years; however, none of the large scale changes that must have occurred in this period has been witnessed since 1970. An attempt was made to relate long- and short-term barrier morphological changes to an overall nearshore wave climate in Kouchibouguac Bay. For this purpose, longshore variations in wave power, normal and parallel with shore, were calculated using computer wave-refraction techniques and wave data characteristic of the southern Gulf and Northumberland Strait.

In Kouchibouguac Bay, greatest wave power values normal to shore are located along the ends of the embayment and adjacent to the three major inlets. Lowest wave power values occur at the inlets themselves and are a function of wave divergence over relict offshore fluvial channels. Longshore wave-power terms show less variation with an overall residual northward component along much of the bay. This northward direction is in contrast to the direction of sediment transport deduced from morphological evidence. It appears that the occurrence of north-northeast and northeast waves is more important in Kouchibouguac Bay. Waves from these directions account for most of the southward component of wave power, a fact which may reflect the influence of storms in the bay.

Longshore sediment transport rates, inferred from residual longshore wave-power values, are quite low within Kouchibouguac Bay. Regardless, these inferred rates can be used together with onshore wave power components to account for long term changes in barrier morphology. Areas of inlet breaching, overwashing, and lagoon infilling occupy positions of higher wave power, while areas of barrier downdrift and inlet sediment accumulation occupy positions where either longshore wave-power values are highest or where longshore wave-power vectors converge. The major exception to this pattern occurs at Richibucto Inlet where man has influenced barrier modification through the building of breakwalls.

Short term changes since 1970 have occurred randomly along the barriers and cannot be linked conclusively to an overall nearshore wave regime. Instead these changes may be determined uniquely by waves of a specific direction and period. Because of this, the significance of one low-frequency storm or series of storm events cannot be ruled out in Kouchibouguac Bay. "Catastrophic" storm events can be invoked for sudden inlet breaching and barrier modification. The occurrence of many such events have an additive effect. Long term barrier island changes are responding to an overall wave climate. A barrier segment may be breached by the catastrophic storm waves only because the shoreline has been eroded repeatedly by previous storms. Some indication of the areas susceptible to barrier plan form change can be obtained from the overall variation in wave power, both normal to, and parallel with shore, throughout Kouchibouguac Bay. Those areas with higher wave power values are more likely to undergo longer lasting modification, but those areas with lower values are more likely to undergo only aperiodic change.

The methodology used in this study should be applicable to other barrier island systems such as the Miramichi and Iles de la Madeleine. Only two constraints limit the wider applicability of this methodology to other shorelines in the Gulf of St. Lawrence and Maritime Provinces. The constraints are obvious from the limitations that have been imposed on results in this paper. The type of bathymetric data available in Kouchibouguac Bay precluded detailed simulation of wave orthogonals around inlets and in nearshore areas. Suitable bathymetric coverage of inlets and nearshore shoals in depths of less than 5 m does not exist for many areas in the Gulf. Nearshore wave-power calculations depend upon accurate bathymetry at these inshore locations. More importantly an accurate wave climatology is needed in the Gulf and Maritimes. Hindcasted statistics, aperiodically collected wave-rider buoy data or ship observations cannot compensate for directional wave data collected from a stationary wave-rider buoy over a period of 3 or more years. If accurate wave period, height and directional statistics existed, the methodology outlined here could prove very useful for the efficient determination of shoreline processes, morphological change and environmental sensitivity assessments.

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