CHAPTER ONE HUNDRED FORTY FOUR

BEACH AND SURF ZONE EQUILIBRIA AND RESPONSE TIMES

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ABSTRACT

Analyses were performed on a 6½ year time series of daily wave data, daily beach state data and monthly beach and surf zone profile data. Beach state changes, which involve the relatively rapid redistribution of sediment already stored locally, are predictable in terms of Dean's (3) simple parameter $\Omega = H_b/(w_s T)$ where H_b is breaker height, w_s is sediment fall velocity and T is wave period. Each of the six beach states has a different equilibrium range of Ω values and the direction of change (erosion or accretion) depends on the departure from the equilibrium association. Empirical eigenvector analyses performed on the profile data permitted separation of different response components. The lower order vectors expressing the grosser aspects of the profile features such as beach volume and surf zone gradient displayed maximum variance at periods in excess of 2 years whereas much shorter response times characterized the higher order components such as bar-trough shapes and asymmetries. We infer that the fast response, and more predictable, components of beach and surf zone change largely involve smaller scale sediment exchanges between the beach and surf zone whereas the slower responses are related to larger scale exchanges between the surf zone and the inner continental shelf.

INTRODUCTION

Beach changes can involve changes in beach <u>volume</u> or beach <u>state</u> or both. Beach state, as used here, refers to the six common beach states (5, 6, 8, 9, 10, 11; Fig. 1). These include the reflective (steep) and dissipative (flat) extremes as well as 4 intermediate states which are (in order of decreasing surf energy): longshore bar-trough (LBT); rhythmic bar-and-beach (RBB); transverse bar-and-rip (TBR); and ridge-and-runnel/low tide terrace (LTT). Each state is dominated by a different set of hydrodynamic mechanisms. At a

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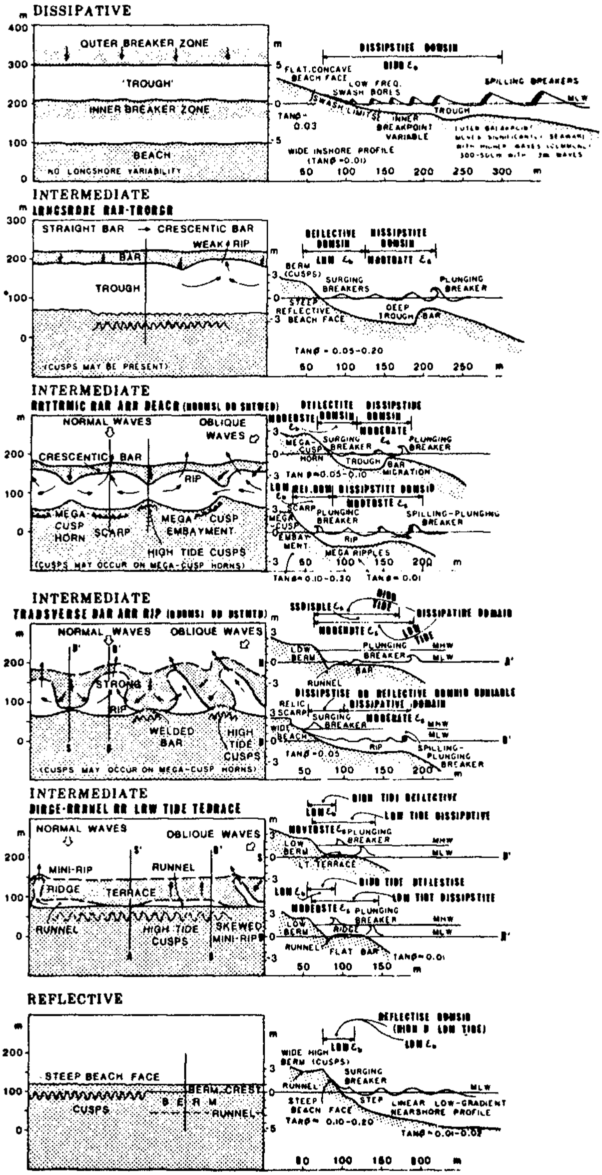

Figure 1. Plan and Profile Characteristics of the Six Common Beach States.

somewbat crude, first order level beach state exhihits a reasonable degree of dependence on Dean's (3) parameter $\Omega = H_b/(w_s T)$ where H_h is hreaker height, T is wave period and w_s is sediment settling velocity (9). However, variations in Ω can only partially explain the short term temporal variations in beach state or in heach profiles. Rates and directions of beach response are governed not only hy tbe short-term history of Ω, but equally hy antecedent beach state. Long-term (> 1 year) cycling of sediment hetween the inner shelf and the surf zone add further complexity to attempts at gaining short-term predictahility.

The purpose of this paper is to present the most recent results in the development of a general model for predicting short-term changes in heach and surf zone morphodynamics, emphasizing moderate to high energy natural systems. To this overall end, we have examined the equilibrium relationships hetween heach state and Ω; rates of change of hoth heach state and heach volume as functions of disequilibrium; and response times and frequency-response characteristics for different types and scales of change.

TECHNIQUES

Time series spanning 6½ years of daily wave data and heach state observations, and biweekly to monthly beach and surf zone leveling transects at 8 locations on the moderate to higb energy Narraheen Beach near Sydney in southeastern Australia, supplemented by shorter time series from other beaches, provided the basic data set of our analyses. The daily data were suhjected to harmonic and spectral analyses to identify dominant response cycles. Using smoothed time series, time derivatives of Ω, heach state and beach volume were estimated. To evaluate the degree to which heach state can be predicted in terms of Ω, discrete discriminant analyses were performed utilizing a record of 1,545 cases. Empirical eigenvector analyses were performed on the beach profile data to characterize the time-varying profile features. Weightings on the dominant eigenvectors were subjected to spectral analyses to determine the dominant frequencies of variation of each vector.

SHORT-TERM CHANGES IN BEACH STATE

A 20-month section of the time series of daily significant wave height, H_s, daily estimated Ω values, daily beach state, and subaerial heach volume, V_b, as observed on mid-Narraheen Beach is shown in Figure 2. From Figure 2, it is apparent that wave conditions and beach state change rapidly whereas suhaerial beach volume responds much more slowly. In addition, any given state can occur at any time of the year regardless of whether subaerial beach volume is normal, accreted, or eroded.

The time interval required for a full-state (i.e. one complete state) response to changing wave conditions averaged 7 days for Narrabeen Beach. Harmonic and spectral analyses show that the largest amount of beacb change is associated with 'cycles' of 70 to 120 days.

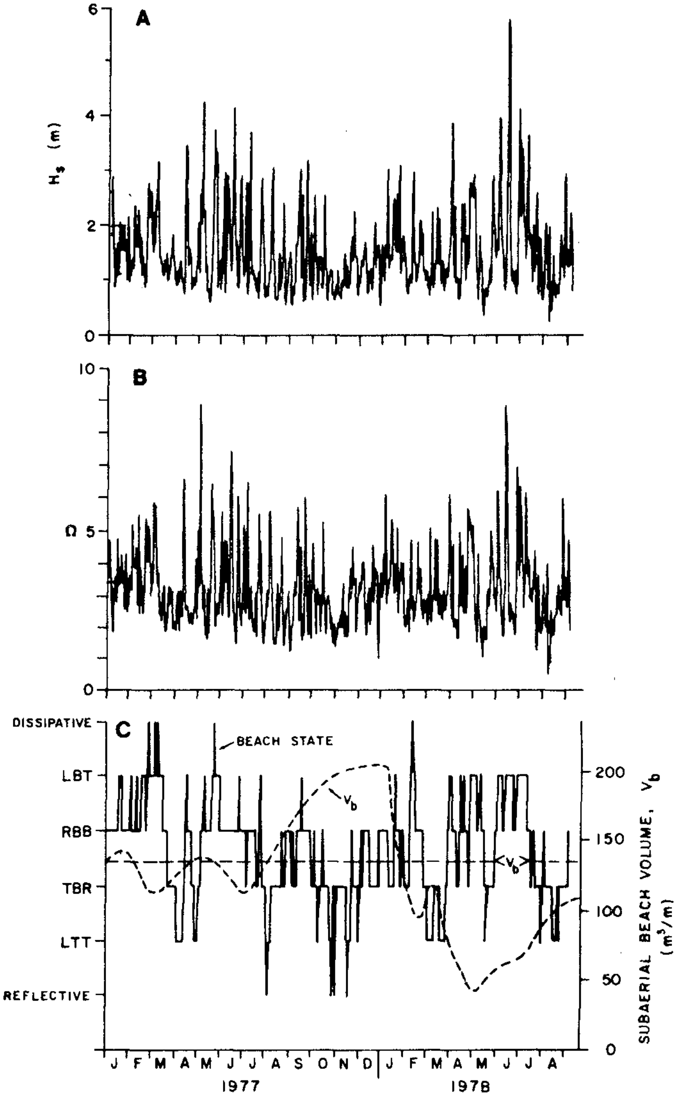

Figure 2. Time series of daily significant deepwater wave height (A), daily Ω values (B), and daily beach state (C). Subaerial beach volume is also shown in C. $\langle V_b \rangle$ indicates the long-term mean subaerial beach volume.

However, a pronounced secondary peak in amplitude of beach state change occurs in the period band of 15-20 days. This response results from the normal passage of pressure systems. In this response band, beach state changes lag changes in Ω by 4 days.

Discrete discriminant analyses were used to test the degree to which day-to-day variability in beach state can be predicted in terms of Ω. Two Ω values were used in the analyses: the immediate value occurring on the day the particular state was observed and a weighted mean value $\bar{\bar{\Omega}}$ expressing recently antecedent conditions. The weighted mean value was computed from

$$\bar{\bar{\Omega}} = \left[\sum_{i=1}^{D} 10^{-i/\phi} \right]^{-1} \sum_{i=1}^{D} (\Omega_i \, 10^{-i/\phi}) \qquad (1)$$

where i=1 on the day before state observation and i=D on D days before observation. The parameter ϕ depends on the rate of memory decay; the weighting factor decreases to 10% at ϕ days before observation. The immediate value of Ω made a negligible contribution to explaining daily beach state changes. However, the antecedent conditions as expressed by $\bar{\bar{\Omega}}$ showed a very strong association when ϕ =5 days and D=30 days.

Table 1 summarizes the means and standard deviations of $\bar{\bar{\Omega}}$ associated with each state. Although the means of $\bar{\bar{\Omega}}$ differ significantly between states, the overlap between similar states (e.g. rhythmic bar and beach and transverse bar and rip) is too large to permit highly successful prediction of all six states. Predictability, in terms of discriminant functions which are overwhelmingly dominated by $\bar{\bar{\Omega}}$, is substantially increased when adjacent and similar pairs of states are combined into fewer classes. To produce three broader groups we combined the reflective extreme with the low-tide-terrace/ridge and runnel state, the transverse bar and rip state with the rhythmic bar and beach state, and the longshore bar-trough state with the dissipative extreme. The rationale for this simplication is discussed more fully by Wright et al. (12). The central tendencies of $\bar{\bar{\Omega}}$ for each of the three recombined groups are presented in Table 2. The probability distributions of $\bar{\bar{\Omega}}$ for each class are shown in Figure 3 from which clear separation can be seen. Predicted state corresponded to the observed state in 68.5% of the 1,545 cases examined when the simplified classification was used. The success rates of predicting the reflective and dissipative end members were 85% and 78% respectively.

By examining cases where the time derivatives of both state and Ω were near zero, it was possible to define the equilibrium conditions associated with each state. The equilibrium values, Ω_e, of each state are summarized in Table 3. Directions of change (erosional or accretionary) are predicted in terms of "instantaneous" or short-term time averaged departures of Ω from the equilibrium value appropriate to the inherited beach state prevailing at the time change begins.

Table 1

Average Associations Between Beach State, Ω, and $\overline{\Omega}$ for Narrabeen Beach

Beach State	Number of Occurrences	Mean Ω	Mean $\overline{\Omega}$	Stan. Dev. Ω	Stan. Oev. $\overline{\Omega}$
Reflective	38	2.33	2.18	0.60	0.32
LTT	233	2.52	2.35	0.80	0.49
TBR	691	3.15	3.16	0.98	0.67
RBB	402	3.34	3.38	1.00	0.65
LBT	170	4.64	4.74	1.55	1.04
Oissipative	11	5.42	5.46	1.47	0.93

Table 2

Average Associations Between Merged Beach State Classes, Ω, and $\overline{\Omega}$ for Narrabeen Beach

Merged Beach States	Number of Occurrences	Mean Ω	Mean $\overline{\Omega}$	Stan. Dev. Ω	Stan. Oev. $\overline{\Omega}$
Refl. & LTT	271	2.50	2.36	0.77	0.46
TBR & RBB	1093	3.22	3.24	0.99	0.67
LBT & Diss.	181	4.69	4.86	1.56	1.05

Table 3

Equilibrium Associations Between Beach State and Ω_e

Beach State	Ω_e Mean	Stan. Dev.
Reflective	< 1.5	----
LTT	2.40	0.19
TBR	3.15	0.64
RBB	3.50	0.76
LBT	4.70	0.93
Dissipative	> 5.5	----

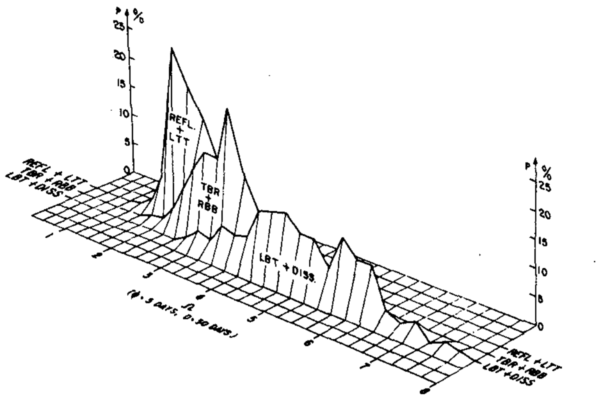

Figure 3. Frequencies of association between $\bar{\bar{\Omega}}$ values and the three merged beach state classes.

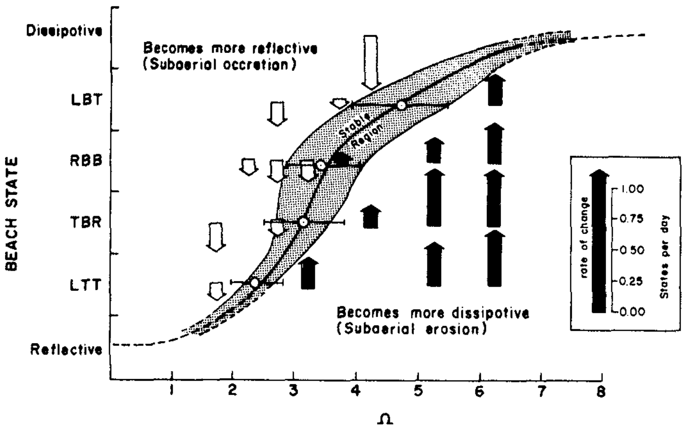

Figure 4. Beach State Equilibria and Directions and Rates of Change. The central curve indicates the mean equilibrium associations between state and Ω. If a beach lies to the right and below the stable region in terms of the combination of preexisting state and prevailing Ω, subaerial erosion will take place to produce more dissipative conditions. If the combination is above and to the left, then subaerial accretion can be expected.

The inferred equilibrium associations and directions of change are indicated by Figure 4. In general, it is possible to predict probable states in terms of recently antecedent wave conditions with reasonable success. Furthermore, the direction of change can be predicted when the instantaneous combination of state and Ω is in sufficient disequilibrium as to lie outside the "stable region" of Figure 4.

VARIATIONS IN BEACH AND SURF ZONE PROFILES

The same 6½ year data set includes monthly beach and surf zone profiles which provide a relatively long time series of subaerial beach volume and profile shape. In contrast to the relatively fast changes in beach state, beach volume changes are slow and involve sediment exchanges across the inner shelf. The largest changes in the subaerial beach volume of Narrabeen Beach have amplitudes in excess of 100 m^3m^{-1} and occur over time intervals of 2 to 4 years. Changes in profile dimensions and shape express in part the relatively rapid changes in state and in part the much slower changes in gross sediment volume.

Empirical eigenvector analyses provided an objective, quantitative characterization of changing profile shapes. Basically, the analysis transforms a set of intercorrelated variables into a new coordinate system in which the axes are linear combinations of the original variables and are mutually orthogonal. Two types of analyses were conducted: (1) in the first ("fixed datum") the eigenvectors express profile variability referenced to a fixed datum; (2) in the second ("floating datum") the profile variability is referenced to the instantaneous position of the shoreline and is independent of absolute degree of accretion or erosion. The latter analyses best express profile shape and can be related to beach state. The lower order eigenvectors (E_1, E_2) express the grosser aspects of the profile such as beach volume, width and gradient. More complex profile features such as bar-trough configurations, asymmetries, and steps are expressed by progressive addition of higher vectors (E_3, E_4, E_5). The additive properties of the vectors are illustrated by Figure 5.

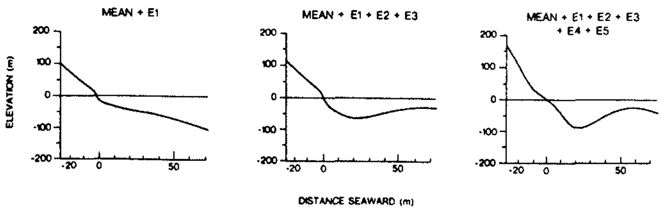

Figure 5. Additive Properties of the Eigenvectors (Floating Datum Case).

The physical meanings of the first four fixed datum eigenvectors are illustrated in Figure 6. Most of the variance in the profile of Narrabeen Beach is accounted for by eigenvector 1 which expresses beach width and sediment volume; that is, in essence, a sand storage function. As illustrated by Figure 6, a positive weighting on eigenvector 1 indicates an accreted profile (relative to the mean) whereas a negative weighting indicates an eroded profile. The amplitudes of profile changes associated with eigenvectors 2-4 are small relative to those associated with eigenvector 1. However, these higher modes of profile behavior are more closely related to profile shape. A positive weighting on eigenvector 2 indicates a steeper beach with a well developed berm fronted by bar-trough topography. A negative weighting corresponds to overall profile flattening.

Figure 7 shows power spectra of the weightings on the four fixed datum eigenvectors. The maximum and only consequential variance in eigenvectors 1 and 2 is seen to occur at periods of two or more years. Temporal variations in eigenvector 1 directly parallel variations in subaerial beach volume (Fig. 2); the weightings on this vector are coherent and in phase between all profiles along Narrabeen Beach indicating that a shore-normal rather than a longshore redistribution of sediment is responsible for the changes.

The floating datum modes of profile variation are independent of absolute sand storage volume and beach width and are therefore better able to describe the behavior of profile shape. Figure 8 shows the nature of the profile shape effects described by the first five floating datum eigenvectors. Table 4 indicates the profile shape "signatures" of each of the six beach states (Fig. 1) expressed in terms the signs of the weightings on the eigenvectors. The first eigenvector expresses the overall flattening (+ weighting) and steepening (- weighting) of the surf zone and beach and thus characterizes the relative degree of dissipativeness or reflectivity of the system. This mode of variation is most effective in discriminating between the two extreme beach states (Table 4). Pronounced bar-trough topography yields positive weightings on both eigenvectors 2 and 3 (Figs. 8 and 5); the absence of bars is expressed by negative weightings on both of these vectors. Accordingly, the strongly barred states (LBT, RBB) are distinguished from the other states on the basis of the weightings on eigenvectors 2 and 3 in combination. Adjacent (in Fig. 1) and somewhat similar intermediate states are discriminated between in terms of the higher vectors. For example, eigenvector 4 distinguishes between the longshore bar trough state (+ weighting) and the rhythmic bar and beach state (- weighting) while eigenvector 5 distinguishes the rhythmic bar and beach state from the transverse bar and rip state.

The results of spectral analyses performed on the time series of the weightings on the floating-datum eigenvectors are shown in Figure 9. The power spectrum of the weightings on eigenvector 1 shows the dominant peak to be centered at periods between 24 and 42 months. This suggests that the largest amplitude variations in overall profile gradient or "dissipativeness" are related to the same long-period processes that produce the major variations in gross sand storage. The existence of a secondary but significant peak at about 2.3 months

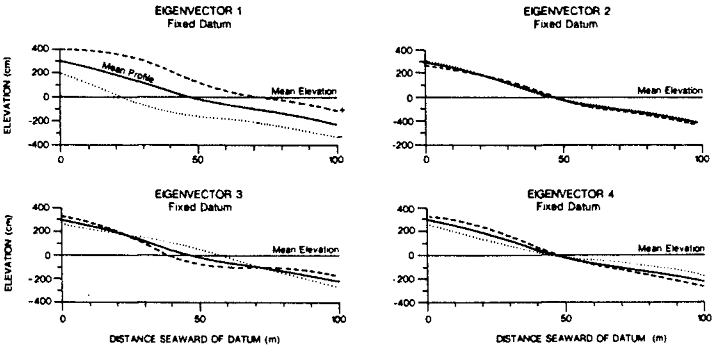

Figure 6. Fixed-datum modes of profile variation for Narrabeen Beach. Positive and negative weightings on the eigenvectors are indicated respectively by the dashed and dotted curves. The solid curve indicates the time-averaged mean profile.

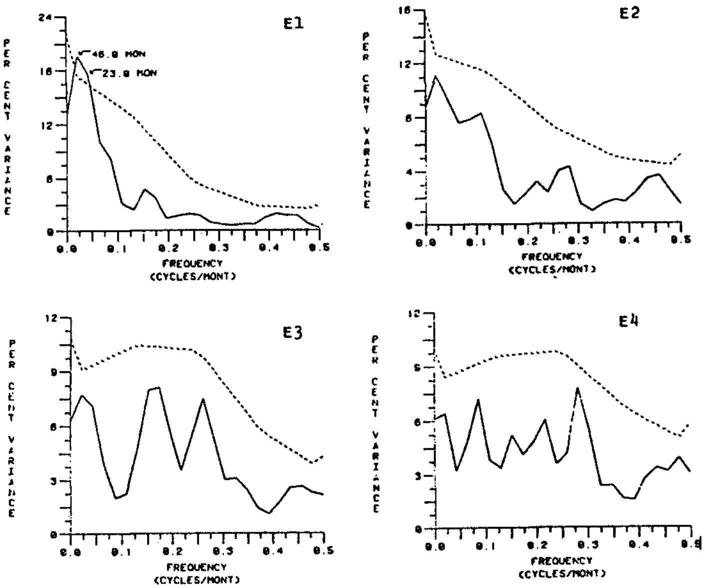

Figure 7. Power spectra of the weightings on the four fixed-datum eigenvectors. The dashed curve indicates the 95% confidence level for spectral peaks.

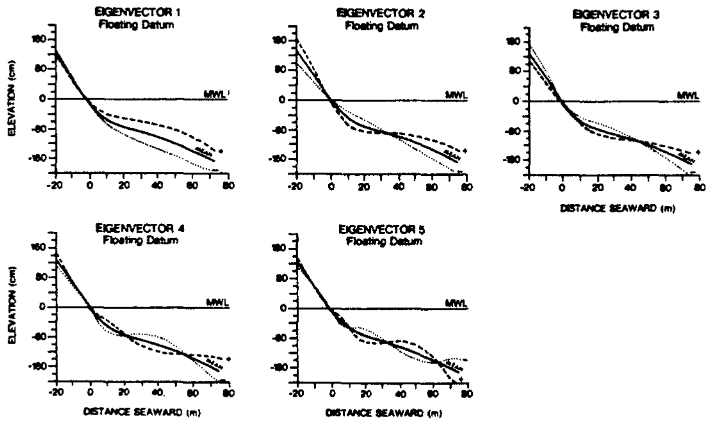

Figure 8. Floating-datum modes of profile variation. Positive and negative weightings are indicated respectively by the dashed and dotted curves.

Table 4. Relationships Between Beach State and the Signs of Weightings on the Five Floating Datum Eigenvectors.

Floating Datum Eigenvector No.	Beach State: Refl.	LTT	TBR	RBB	LBT	Diss.
E1	-- *	-	~0	~0	-	++ *
E2	-	-	+	+	+	-
E3	-	-	~0	+	+	+
E4	+	~0	~0	-	+	~0
E5	+	+	+	-	~0	-

*Extreme negative and extreme positive weightings are indicated by -- and ++ respectively.

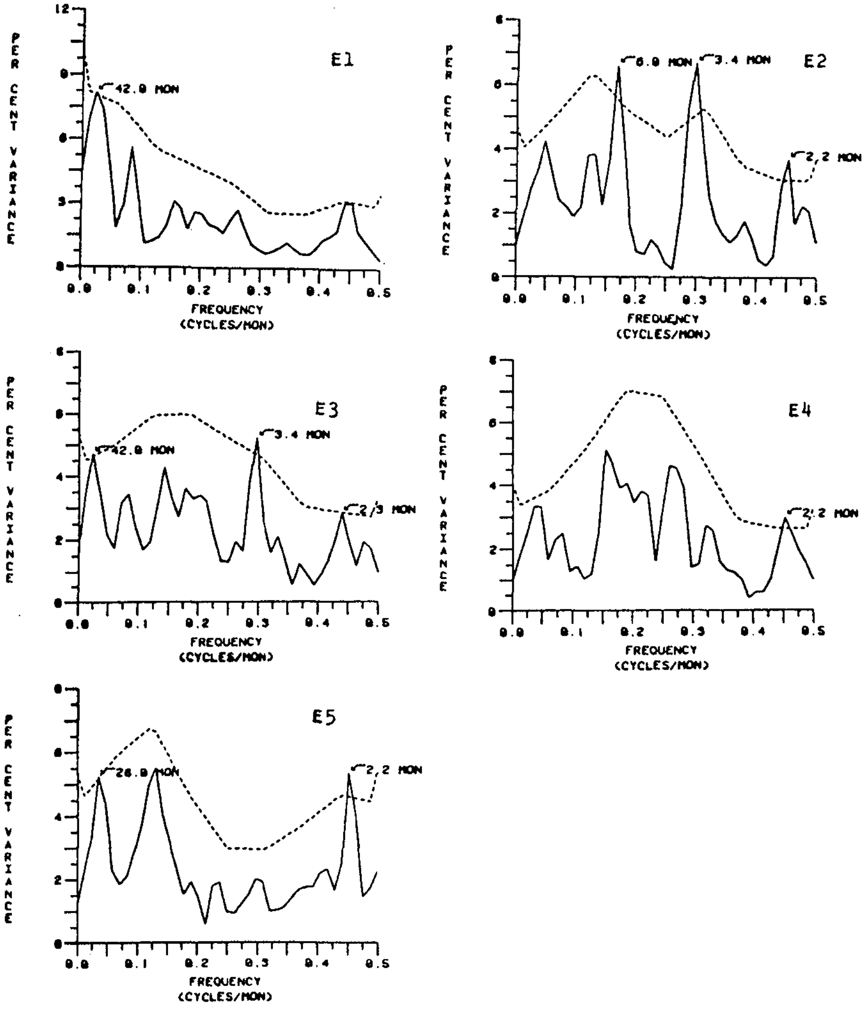

Figure 9. Power spectra of the weightings on the five floating-datum eigenvectors.

indicates that profile gradient is also responsive to higher frequency forcings. The dominant variations in eigenvectors 2 through 5 occur at periods of 2 to 6 montbs. This corresponds to the period band of the largest amplitude fluctuations in beach state as discussed earlier. However, it must be noted that eigenvectors 2-5 all exhibit appreciable variance at periods of 2 years or more. We can infer from tbis that even the higher-order aspects of profile shape --and hence beach state-- are significantly overprinted by slow oscillations in inshore sediment storage.

DISCUSSION AND CONCLUSIONS

The state, profile configuration, and sand storage of a beach and surf zone system as observed at any given time are consequences of the time integration of numerous antecedent processes having different space and time scales. We have attempted to deal, albeit superficially, with part of the complexity of this problem by separating the total response into components, each of which has its own cbaracteristic space scale and temporal frequency. Others before us have performed simlar analyses on beach profiles with the aim of elucidating seasonal (e.g. 1, 4, 7) as well as tidal cycle (e.g. 2) responses. We are concerned not only with the temporal behavior of the profile and of the volume of sediment stored therein but equally with the temporal behavior of the three-dimensional beach and surf zone state. Our interest in beacb state lies in the fact that beach state is an indicator of the dominant surf zone process signature (9) and influences the mechanisms and probability of beach erosion or accretion (8). Furthermore, changes in beach state permit at least short-term quasi-equilibrium with changes in wave conditions to be achieved, by virtue of surf zone process modification, without major changes in the gross sand storage properties of the beach. This has the potential of temporarily arresting or impeding the large-scale response of the profile to larger scale (larger than scale of surf zone) and longer term disequilibrium. Conversely, bowever, beach state is subject to changes induced by large scale, low frequency sediment fluxes. For example, the introduction of sediment into a surf zone from alongshore or from seaward of the surf zone can cause a reflective or intermediate beach which is in equilibrium with low to moderate waves to become dissipative.

The range, rate and frequency of response of a particular mode of beach variability depends in part on the frequency and intensity of the forcing involved, in part on the degree of disequilibrium induced by changing morphodynamic conditions, and in part on the scale and associated "time constant" of the mode of variability. Modes of change which involve the redistribution of relatively small quantities of sediment over relatively small distances bave short response times in comparison to modes, sucb as the sand storage function for example, which involve large excbanges of sediment and require more total work. Beach state cbanges can take place, at least within a limited range of intermediate states, by means of localized short-range redistribution of the sediment already contained in tbe surf-zone and intertidal beach. Accordingly, and as illustrated by Figure 2, beach state can change rapidly and frequently and, for this reason, can be rougbly predicted in terms of recently antecedent wave conditions. Major shifts in state from fully dissipative to fully reflective or vice versa are more closely linked to total inshore sand storage and to overall flattening and steepening and are thus much lower in frequency.

In the case of the moderate energy Narrabeen Beach dealt with in this paper, we see that beach state and the associated higher modes of profile change respond quickly whereas gross sediment storage and overall inshore gradient respond slowly. Changes in the fixed-datum sand storage function and to some extent in the floating datum gradient function (eigenvector 1) involve the import and export of large quantities of sand to and from the beach and surf zone system. Since Narrabeen Beach is headland-bounded, these sediment transfers must occur in the cross-shore dimension and must thus involve exchanges between the surf zone and the inner shelf. As illustrated conceptually by Figure 10, we infer that the slow-response modes of variability involve large-scale cycling of sediment across the inner shelf. On the Australian east coast the "closure" depth to which the sediment exchange is active is probably between 20 m and 30 m. It is obviously shallower on less energetic coasts. The actual physical processes responsible for alternating shoreward and seaward transport over the inner shelf remain to be identified.

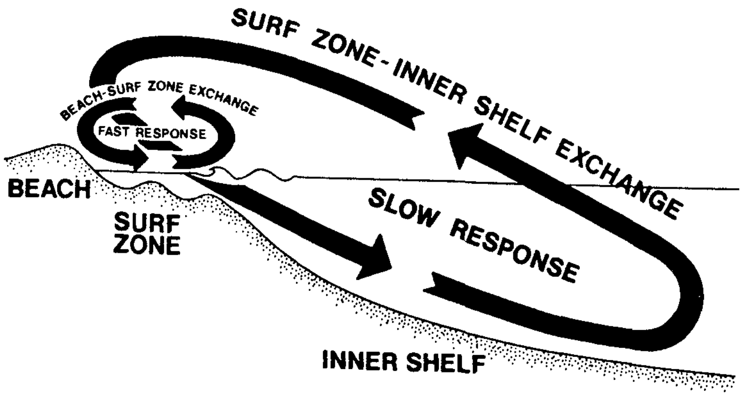

Figure 10. Scales and frequencies of beach, surf zone, and inner shelf responses. Rapid, relatively high frequency temporal changes in beach state and higher-order modes of profile variability largely involve the short-range redistribution of sediment already contained within the beach/surf-zone system. Low-frequency variability in sand storage and associated effects involves large-scale and slow exchanges of sediment between the surf zone and the inner shelf.

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