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Relationship between beach profiles and waves at Duck, North Carolina, determined by canonical correlation analysis

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Abstract

An 11-year long measurement time series of waves and profiles from Duck, North Carolina, was analyzed using canonical correlation analysis (CCA) in order to determine the covariability between waves and profile response. The main objectives of this analysis were (1) to detect simultaneously occurring patterns in the wave and profile data and, if possible, give such patterns a physical interpretation to increase the insight into the governing processes, and (2) to investigate the possibility to use CCA in a predictive mode with the aim to calculate the profile response from the waves. The profile shape itself and the change between consecutively surveyed profiles were correlated with both the offshore (deep-water) and nearshore wave conditions. In the offshore, the waves were described by composite probability density functions (pdf) derived based on the measured wave conditions prior to a profile survey. Nearshore wave conditions were calculated using a random breaker decay model and averaged local wave properties were used as input to the CCA. The profile response displayed significantly higher correlation with the nearshore wave properties as compared to the offshore waves, and the highest correlation was found between the profile shape and the mean ratio of breaking waves for the time period preceding the profile survey. The CCA using nearshore wave properties indicates a potential for predicting the profile response with an acceptable degree of accuracy once a regression matrix relating the profiles to the waves has been established that represents the typical variability at the site.

Keywords: beach profile; statistical models; canonical correlation analysis, empirical orthogonal functions; wave transformation; energy dissipation; field data

1. Introduction

The interaction between waves and beach profile response in the nearshore is a highly complicated phenomenon resulting from many different processes acting at widely varying scales in time and space (De Vriend, 1991; Larson and Kraus, 1995). It is often difficult to derive simple, deterministic equations or models to describe the relationship between the waves and the profiles, except in well-defined situations when a few processes control the profile response. Even detailed, physically based models typically produce predictions that are not satisfactory over longer time periods because of problems associated with adequately describing the governing processes so

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that beach changes induced by small net gradients are accurately reproduced. Thus, there is a need to employ sophisticated statistical models, both for predictive purposes and for identifying patterns and structures in the data that can be linked to the physical processes at hand. Canonical correlation analysis (CCA) is one such advanced statistical technique that can be used to determine dominant patterns of covariability in two data sets and their relationship (Barnett and Preisendorfer, 1987; Graham et al., 1987a).

CCA was developed by Hotelling (1936) for application in the social sciences and Glahn (1968) was the first to use this technique for analysis of geophysical data. A wider use of CCA in geophysical applications, especially in meteorology and oceanography, started in the middle of the 1980s with pioneering work by Barnett and Preisendorfer (1987). They attempted to forecast the air temperature over United States from sea surface temperature (SST) and sea level pressure (SLP) using CCA. Graham et al. (1987b) constructed CCA models for predicting the equatorial Pacific SST from the tropical wind field and near-global SLP field. Other recent studies on similar topics are presented in Bretherton et al. (1992), Barnston and He (1996), and Shabbar and Barnston (1996). Singular Value Decomposition (SVD) is sometimes used as an alternative to CCA for finding coupled patterns in two data sets (Wallace et al., 1992; Cheng and Dunkerton, 1995). In SVD, the patterns are derived by maximizing the cross-covariance between the data sets, whereas in CCA the cross-correlation is maximized instead. Since correlation is a better measure of linear association than covariance, CCA is often more appropriate to apply, although this is not always the case (Cherry, 1996). To the authors' knowledge, no application of CCA to analyze or predict coastal evolution exists to date. SVD is sometimes used in coastal applications as an efficient algorithm for empirical orthogonal function (EOF) analysis (Winant et al., 1975; Aubrey, 1979).

In this study, simultaneously collected data on waves and beach profiles from the US Army Field Research Facility at Duck, North Carolina, (Howd and Birkemeier, 1987; Lee and Birkemeier, 1993) were used to investigate the relationship between the waves and the profile response over a longer time period. The data encompassed profile surveys taken along four lines approximately biweekly during 11 years and spectral wave properties (significant height and peak period; incident wave angle was not available) recorded at least every 6 h during the same period. In the present study, only profile data from survey line 62 (see Howd and Birkemeier, 1987) will be discussed, although the other lines displayed similar results in the analysis. The largest number of surveys were taken along this line (340 surveys in total), in most cases from the dune region out to a water depth greater than 8 m. The waves were measured in 18-m water depth and these measurements were used to derive the wave properties employed in the CCA.

Initially, the analysis focused on directly linking the profile response to the offshore waves, which were obtained by backing out the measured waves to deep water neglecting refraction. In order to represent the offshore waves, probability density functions (pdf) were derived for different quantities such as wave height, wave energy flux, wave steepness, and the dimensionless fall speed (Dean, 1973). A clear correlation was obtained in the CCA for the lowest modes, but the relationships were not significant enough to indicate a predictive potential. The next step was to carry out the analysis with nearshore waves, i.e., to derive representative wave properties across the profile using a random wave transformation model. This greatly enhanced the correlation between the waves and the profile response indicating a possibility to use CCA for predictive purposes, if nearshore wave conditions are employed.

In the following, a brief summary is first given of the theory behind CCA and some description of how it was applied in this study. Then, a discussion is provided on the derivation of the offshore wave input to the CCA, followed by a presentation of the results of the analysis between profile response and offshore waves. A brief introduction is provided to the random wave transformation model and how it was used to derive nearshore wave properties. The results of the CCA between the profiles and the nearshore wave properties are presented and a discussion is provided on the potential for using these results to predict profile evolution based on the waves. Finally, some concluding remarks are given on the observations made from the CCA and how it can be related to the physical processes governing profile change.

2. Canonical correlation analysis (CCA)

CCA may be used to investigate if there are any pattern that tend to occur simultaneously in two different data sets and what the correlation is between associated patterns (Graham et al., 1987a). The main idea is to form a new set of variables from the original two data sets so that the new variables are linear combinations of the old ones and maximally correlated. If the two original data sets are denoted $\mathbf{Y}$ and $\mathbf{Z}$, the new transformed variables in matrices $\mathbf{U}$ and $\mathbf{V}$ have maximally correlated column vectors for the same index and zero correlation for differing indices. Furthermore, the column vectors in $\mathbf{U}$ and $\mathbf{V}$ are orthonormal. In the present analysis, $\mathbf{Y}$ is the wave data matrix and $\mathbf{Z}$ the profile data matrix having the sizes $nt \cdot ny$ and $nt \cdot nz$, respectively. The matrix dimension nt is the number of values in time (must be the same for $\mathbf{Y}$ and $\mathbf{Z}$), and ny and nz are the number of values in space (or corresponding) for matrices $\mathbf{Y}$ and $\mathbf{Z}$, respectively.

The desired weights for transforming $\mathbf{Y}$ into $\mathbf{U}$ are given by the solution to the eigenvalue problem (Graham et al., 1987a):

$$\left[(\mathbf{Y}^{\mathrm{T}}\mathbf{Y})^{-1}(\mathbf{Y}^{\mathrm{T}}\mathbf{Z})(\mathbf{Z}^{\mathrm{T}}\mathbf{Z})^{-1}(\mathbf{Z}^{\mathrm{T}}\mathbf{Y}) - \mu^2 I\right] = 0 \tag{1}$$

where μ^2 denotes the eigenvalues and the superscript T is transpose. The eigenvalue gives the squared correlation between the corresponding temporal amplitudes of the canonical modes (the column vectors in $\mathbf{U}$ and $\mathbf{V}$), and the associated eigenvectors $\boldsymbol{R}$ yield the transformation $\mathbf{U} = \mathbf{Y}\boldsymbol{R}$. A similar eigenvalue problem as given by Eq. (1) defines the transformation of $\mathbf{Z}$ into $\mathbf{V}$ having the same μ^2-values and eigenvectors $\boldsymbol{Q}$, which produces the other transformation $\mathbf{V} = \mathbf{Z}\boldsymbol{Q}$. The spatial amplitudes (G and H) of the canonical modes are obtained as $G = \mathbf{Y}^{\mathrm{T}}\mathbf{U}$ and $H = \mathbf{Z}^{\mathrm{T}}\mathbf{V}$. Thus, the original data sets are expressed as $\mathbf{Y} = \mathbf{U}G$ and $\mathbf{Z} = \mathbf{V}H$.

EOFs are often used in a pre-processing step to CCA in order to reduce the noise in the data and to become familiar with the general structure of the data. The data sets ($\mathbf{Y}$ and $\mathbf{Z}$) are expressed in terms of their EOFs and a certain number of modes are selected to represent the data before the CCA is carried out. Thus, the data sets may be expanded as $\mathbf{Y} = AE^{\mathrm{T}}$ and $\mathbf{Z} = BF^{\mathrm{T}}$, where A and B contains the temporal EOFs (or, principal scores) and E and F the spatial EOFs for Y and Z, respectively. A limited number of EOF modes na ($< ny$) and nb ($< nz$) are selected to represent $\mathbf{Y}$ and $\mathbf{Z}$, respectively, when performing the CCA.

Based on the correlation between the dominant patterns in the profile and wave data established through the CCA, a regression matrix may be derived that relates the profiles to the wave properties. Thus, if the wave properties are known, the profile response may be predicted by employing the regression matrix. Having a wave matrix $\mathbf{Y}_{\mathrm{p}}$ (measured or simulated), the associated profile data matrix $\mathbf{Z}_{\mathrm{p}}$ is given by:

$$\mathbf{Z}_{\mathrm{p}} = \mathbf{Y}_{\mathrm{p}}\Psi \tag{2}$$

where,

$$\Psi = GSF^{\mathrm{T}} \tag{3}$$

and $S = \mathbf{U}^{\mathrm{T}}B$. This technique was evaluated by investigating how well the profile shape could be predicted from the wave properties using a limited number of CCA modes in the regression procedure.

3. Offshore wave properties

The first step in the CCA was to directly correlate the profile response to the offshore (deepwater) waves. The purpose was to investigate whether representative wave statistics in the offshore, such as the pdfs for different waves quantities, exhibited any relationship with the observed patterns of variation in the profile response. The motivation for employing pdfs in the CCA was the hypothesis that by correctly representing the statistical distribution of the wave forcing (e.g., height or energy), a marked coupling could be found with the local profile response. In other words, a pdf dominated by small waves would mainly affect the profile in the inshore portion and vice versa. As expected, the CCA confirmed this hypothesis (discussed in the next section), but strong relationships between waves and profile response could only be established for the lower CCA modes.

The wave data available consisted of energy-based significant wave height (H_{mo}) and peak spectral wave period (T_{p}) measured in 18-m water depth, whereas no information on incident wave angles was available. Deepwater wave quantities were calculated by backing out the waves to deep water neglecting refraction in order to obtain more general relationships. The waves were recorded at least every 6 h, but often more frequently. Since the profiles were surveyed biweekly on the average, about 100 wave measurements were typically available between surveys. In order to derive a pdf representative for the time period preceding a specific profile survey (to be used in the CCA), it was assumed that a Rayleigh pdf could characterize the statistical wave conditions during an individual wave measurement. Thus, the root-mean-square (rms) wave height in deep water (H_{rmso}) was obtained from $H_{\mathrm{rmso}} = 0.707 H_{\mathrm{mo}}$. A composite pdf ($p_N$) was then derived by superimposing the individual pdfs that were available for the measurement period between surveys (Larson and Kraus, 1995):

$$p_N(H) = \frac{1}{N} \sum_{i=1}^{N} \frac{2H}{H_{\mathrm{rmso},i}^2} \mathrm{e}^{-\left(\frac{H}{H_{\mathrm{rmso},i}}\right)^2} \tag{4}$$

where H is the wave height, N the number of individual wave measurements between surveys (typically 100, as stated above), and i an index. The superposition carried out in Eq. (4) implies that all pdfs derived from the individual wave measurements (H_{rmso}) are given equal weight.

Composite pdfs used in the correlation were not only computed for the wave height, but also for the wave energy flux, dimensionless fall speed (H/wT, where w is sediment fall speed and T wave period), and wave steepness (H/L, where L is wavelength). The individual pdfs for these quantities were derived by transforming the Rayleigh pdf for H using the relationship that exists between the quantity and H. For example, using linear wave theory the wave energy flux F is given by $F = 1/8 \rho g H^2 C_{\mathrm{g}}$, where ρ is the water density, g the acceleration of gravity, and C_{g} the group speed. Using this relationship and the Rayleigh pdf, the following pdf is obtained for F:

$$p(F) = \frac{1}{F_0} \mathrm{e}^{\frac{F}{F_0}} \tag{5}$$

where $F_0 = 1/8 \rho g H_{\mathrm{rmso}}^2 C_{\mathrm{g}}$. After the derivation of the individual pdf for F, a composite pdf was obtained in accordance with Eq. (4).

Wave period did not enter directly in the analysis when Eq. (4) was used, although the period affected the transformation of the waves out to deep water. However, for the other wave-related quantities investigated, T_{p} entered in the quantity and the measured value was used as a representative value for the associated Rayleigh pdf. When applied in the CCA the composite pdfs were discretized in about 50 intervals (equal to the number of columns *ny* in the **Y** matrix), which was enough to provide a good resolution over the probability interval of significance.

4. Predictions of profile change based on offshore waves

Fig. 1a displays a typical subset of measured profiles along line 62 that were used in the CCA (166 profiles shown). Only surveys that extended from the dune region out to a water depth of about 8 m were included in the analysis. Pairs of surveys were investigated simultaneously in order to quantify profile change and to evaluate the dependence of profile shape on the prevailing waves for a well-defined time period. If the time period between two consecutive surveys was too long ($>$ 20 days), the survey pair was not included in the analysis in order to capture elevation changes over a reasonable period. Fig. 1b shows the corresponding composite pdfs for the wave height valid for the time period between surveys and obtained by summing over a large number of Rayleigh pdfs according to Eq. (4). Thus, Fig. 1a and b represents typical input data sets for the CCA performed based on the offshore waves. In the analysis, not only the profile shape itself was correlated with the wave conditions, but also the elevation change and absolute elevation change between consecutive surveys (as well as the rate of

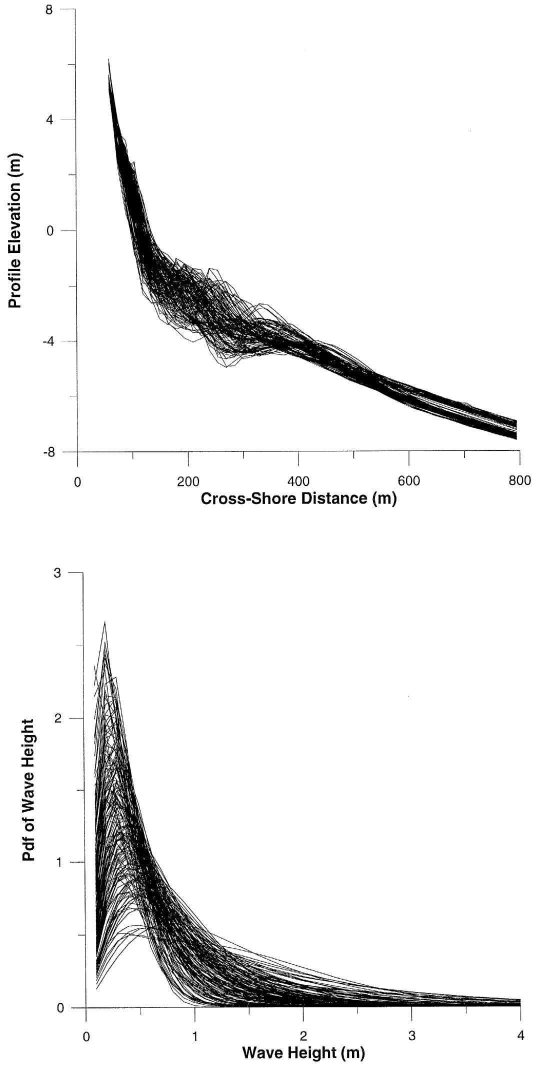

Fig. 1. Time series of (a) beach profiles and (b) probability density functions for deep-water wave height measured at Duck, North Carolina, typically used as input in the CCA analysis.

elevation change). As descriptor of the wave conditions, composite pdfs for the wave height, wave energy flux, dimensionless fall speed, and wave steepness were employed, as mentioned before, all at deepwater conditions.

Before employing the CCA, the data sets were developed in terms of their EOFs to reduce the noise in the data. In general, three to five EOF modes were sufficient to represent most of the variation in the data sets. Fig. 2a displays the three first spatial EOFs (E_1–E_3) for the profile data in Fig. 1a that together explained about 75% of the variation in the data (the time mean was subtracted before analysis in all data sets; for comparable EOF analyses of the Duck data see Larson and Kraus, 1994 and Lee, 1994). Similarly, Fig. 2b shows the three first EOFs (F_1–F_3) for the wave pdfs in Fig. 1b (explained more than 95% of the variation). The EOFs describing the profiles shapes are quite complex due to the presence of one or several longshore bars at Duck. Since the spatial

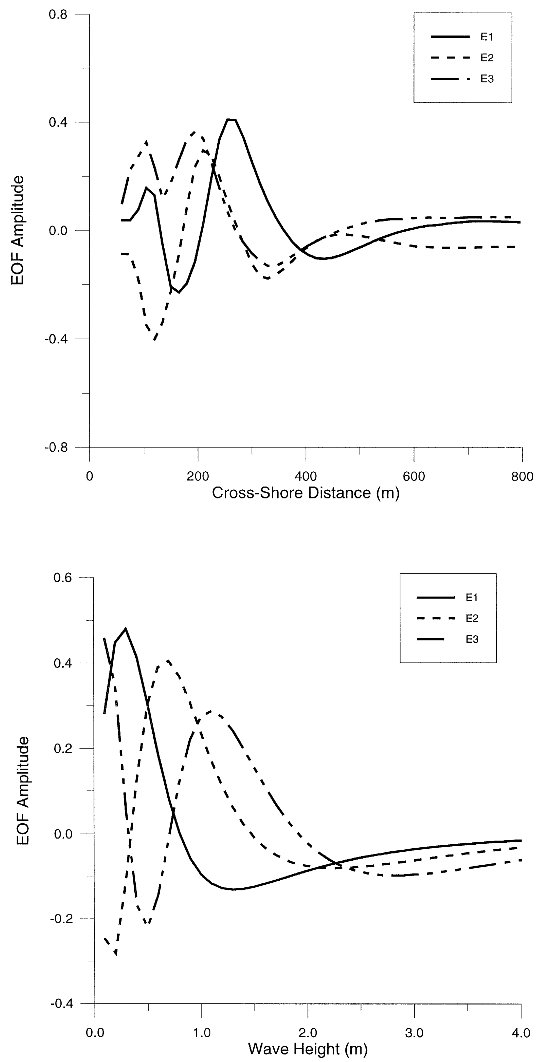

Fig. 2. The first three EOFs ($E_1 - E_3$) determined from measured (a) beach profiles and (b) probability density functions for deep-water wave height.

EOF shapes represent the influence of the bars, these shapes may be used for quantifying mean properties of the bars (compare Larson and Kraus, 1994). Furthermore, the temporal EOFs may be analyzed to determine time scales of bar response and oscillatory cycles.

The first EOF (E_1 in Fig. 2a; explained 31% of the variation) reflects the presence of a single bar that receives contributions from areas both landward and seaward of it. The second EOF (E_2; 25%) characterizes a profile with a double bar and E_3 (21%) may be related to the exchange of material across the profile during major storm events (such events typically cause severe erosion on the foreshore and in the dune region, which implies marked change in the shoreward portion of the profile as represented by E_3). The EOFs associated with the wave pdfs (Fig. 2b) mainly represent seasonal variations in the wave climate and the effects of severe storms (F_1, F_2, and F_3 explained 84%, 13%, and 2% of the variation, respectively). The temporal EOFs clearly exhibit seasonal fluctuations (not shown here), which could be seen in spectral analysis of the signal.

Applying CCA for the two data sets in Fig. 1a and b produced a maximum correlation of 0.41 between $\mathbf{U}_1$ and $\mathbf{V}_1$ (temporal amplitudes of the first CCA modes). The CCA modes showed that the shift of material between the foreshore and the bar area is related to an increase in the probability of higher waves in the pdf (and vice versa; compare Fig. 3b and c, to be discussed later). Higher waves will erode the inshore portion of the profile and deposit material in the bar region, which the observed correlation clearly displayed. Correlating the profile shape with the wave height pdf preceding the survey is based on the assumption that the shape adjusts rapidly to and is mainly a function of the waves as described through the pdf. If the change in elevation between

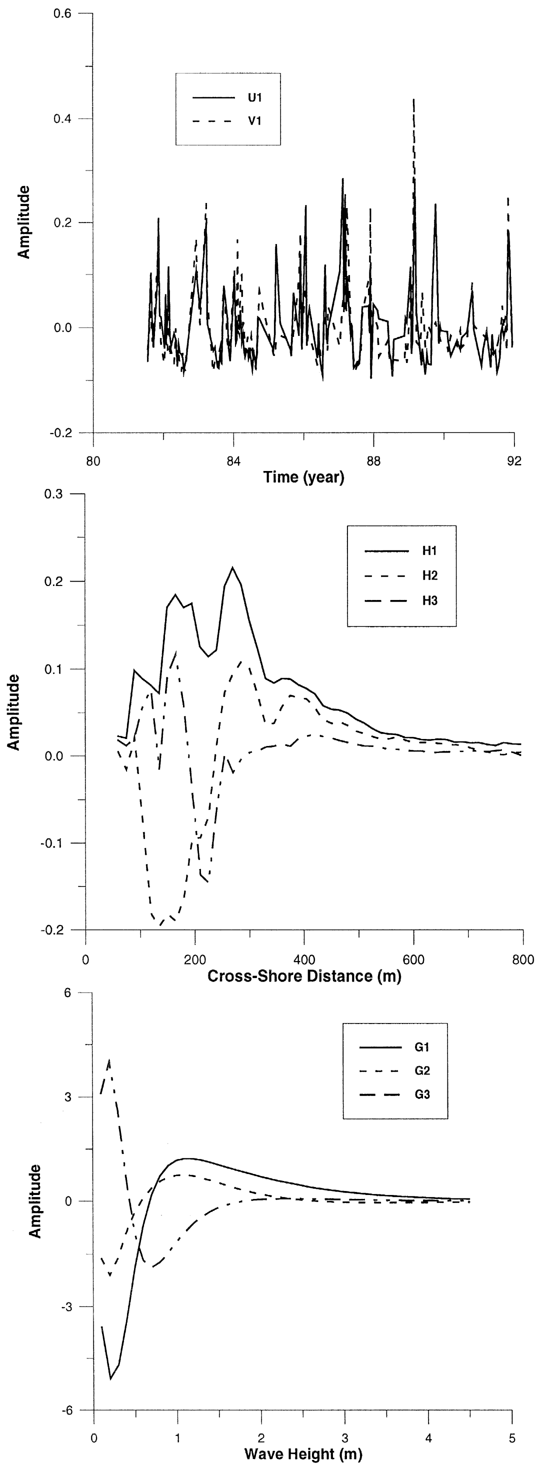

Fig. 3. Results of the CCA analysis between offshore wave height probability density function and absolute elevation change per unit time: (a) temporal amplitudes of the first CCA modes ($\mathbf{U}_1$ and $\mathbf{V}_1$), (b) spatial amplitudes of the first three CCA modes for absolute elevation change per unit time ($H_1 - H_3$), and (c) wave height amplitudes of the first three CCA modes for offshore wave height probability density function ($G_1 - G_3$).

consecutive profiles was used instead of the profile shape itself, the correlation between $\mathbf{U}_1$ and $\mathbf{V}_1$ dropped to 0.37. However, taking the absolute elevation change yielded an increase in the correlation to 0.63. This marked increase indicates that the magnitude of elevation change (quantified by the absolute values) is much easier to relate to the waves than the change itself, which is because the latter also includes the direction of the change (positive or negative). The pdfs derived for the other quantities (wave energy flux, dimensionless fall speed, and wave steepness) did not produce notably higher correlations than the wave height pdf and will not be discussed in detail here.

The highest correlation (0.70) between the temporal amplitudes of the first CCA modes was obtained when the absolute elevation change per unit time was correlated with the wave height pdf. Fig. 3a gives a plot of $\mathbf{U}_1$ and $\mathbf{V}_1$ for the studied 11-year long time series. The correlation for the higher modes decreased rapidly, and for $\mathbf{U}_2$ and $\mathbf{V}_2$ it was only 0.27. Fig. 3b and c display the spatial amplitudes (or equivalent) of the three lowest canonical modes for the absolute elevation change (H_1–H_3) and the wave height (G_1–G_3), respectively. Mode H_1 illustrates the absolute change in the elevation that is associated with variations in the offshore composite wave pdf as given by G_1. Note that H_1–H_3 modify the mean value of the absolute elevation change, so that the overall value is always positive. Thus, H_1 implies a general decrease or increase across the profile of the absolute elevation change when G_1 causes a decrease or an increase, respectively, in the wave pdf. The higher modes H_2 and H_3 are associated with more complex changes in the wave pdf determined by G_2 and G_3, which also imply more complex modifications of the absolute elevation change. This is not completely unexpected since the application of CCA using the offshore waves corresponds to a zero-order model, i.e., a model with no intrinsic dynamics (De Vriend, 1991). By employing a wave transformation model, a more realistic representation of the forcing is obtained that includes the effect of the profile shape preceding a certain event.

Efforts were made to use the derived regression matrix between profiles and offshore waves (compare Eqs. (2) and (3)) for prediction of the profile evolution. However, because of the overall fairly low correlation, except for the lowest modes, these attempts did not produce satisfactory predictions. Thus, the decision was made to calculate nearshore wave properties using a mathematical model, and then correlate these properties to the profile response.

5. Nearshore wave properties

The previous analysis, which aimed at relating the beach profiles directly to the offshore wave conditions for the time period preceding the profile survey, provided a marked correlation between profiles and waves only for the first CCA modes with maximum absolute values on the correlation coefficient (r) in the range 0.4–0.7, depending on the quantities selected in the analysis. In order to find patterns in the profile and wave data that were more strongly related, local wave properties (varying across the profile) were derived and correlated with the profile response. It was hypothesized that profile elevation and change in profile elevation are more correlated with local wave properties than with offshore waves characterized through an overall measure such as the wave pdf. However, since detailed measurements of the local waves were not possible to obtain at the necessary spatial and temporal scale, a numerical model was employed to calculate wave transformation across the profile. Representative wave measures were derived from these calculations and correlated with the profile data, using the profile elevation as well as the change in profile elevation (and its rate) between consecutive surveys.

The random wave decay model developed by Larson (1995) was used to calculate local wave properties based on the measured waves. This model is a generalization of the monochromatic wave decay model by Dally et al. (1985) and it can handle random waves in an efficient and compact manner. The governing equations may be written:

$$\frac{\mathrm{d}F_{\mathrm{rms}}}{\mathrm{d}x} = \frac{\kappa}{d}\left(F_{\mathrm{rms}} - F_{\mathrm{stab}}\right) \tag{6}$$

in which,

$$F_{\mathrm{rms}} = \frac{1}{8}\rho g H_{\mathrm{rms}}^2 C_{\mathrm{g}} \tag{7}$$

$$F_{\mathrm{stab}} = \frac{1}{8}\rho g\left[(1-\alpha)H_{\mathrm{n}}^2 + \alpha\Gamma^2 d^2\right] \tag{8}$$

where F_{rms} is the wave energy flux based on the rms wave height for breaking and non-breaking waves (H_{rms}), x is a cross-shore coordinate, d is the total water depth, α is the ratio of breaking waves, H_n is the rms wave height for non-breaking waves, and κ ($=0.15$) and Γ ($=0.40$) are empirical coefficients in the Dally model. In order to close the above system of equations α and H_n have to be specified, which depends on the pdf controlling the waves (Larson, 1995). A Rayleigh pdf was assumed here for the individual wave height measurements in the offshore (also, for each measurement the assumptions were made of normal incident wave angle to shore and a random wave field narrow-banded in frequency). For a profile where the water depth increases monotonically with distance offshore, the model by Larson (1995) produces identical results to a full Monte Carlo simulation using a wave-by-wave approach Dally (1992). However, for a non-monotonic profile (e.g., a barred profile) an empirical coefficient is needed to reproduce wave reforming (see Larson, 1995 for a more extensive discussion).

By solving Eqs. (6)–(8), local wave properties were obtained at locations across shore corresponding to the survey resolution. Wave input was available typically every 6 h and to derive representative wave properties between consecutive profile surveys averages were taken based on all calculations carried out between surveys. The profile in the beginning of such a pair of surveys was used in the wave transformation calculations. Mean wave properties employed in the CCA were energy dissipation, ratio of breaking waves, and rms wave height (all these quantities were calculated as averages based on the transformed individual waves between survey pairs). These properties were correlated with the profile at the end of the period, defined by a pair of surveys, or with the change in profile elevation between the survey at the beginning and the end of the period.

EOFs were used in a pre-processing step to the CCA, as discussed before, in order to reduce the noise in the data. Also, if the number of wave measurements between a pair of surveys fell below a specified criterion, these data were disregarded in the analysis (typically about 170 profiles were used in the analysis, covering most of the active part of the profile). The wave transformation calculations included setup/setdown computed from the cross-shore momentum equation, but no attempt was made to specifically model the swash zone. Thus, the wave calculations proceeded as far up on the foreshore as possible according to the setup, after which linear interpolation down to zero at the next shoreward calculation point was applied. Water level change due to tide or wind setup was not included which most likely contributed to the scatter when applying the CCA analysis.

6. Predictions of profile change based on nearshore waves

CCA was first employed to correlate the profile shape with the mean energy dissipation calculated based on the waves measured during the period preceding a specific profile survey. Energy dissipation due to breaking waves are intimately linked to the mobilization of sediment as well as the development of the sediment concentration profile. This quantity has been successfully employed in calculating the net cross-shore sediment transport rate (Kriebel and Dean, 1985; Larson and Kraus, 1989). The correlation (r) was 0.77, 0.74, and 0.65 between the first, second, and third CCA temporal modes, respectively. Thus, this analysis shows, as expected, that local wave properties exhibit a much closer relationship with the profiles than what the overall offshore wave quantities did. Fig. 4a and b display the temporal amplitudes of the first and second modes, respectively, for the profile elevation and dissipation. The high correlation between associated modes is clearly visible as well as the variabilities at many different temporal scales. In Fig. 5a, the spatial amplitudes of first three modes are shown for the energy dissipation, while corresponding modes are displayed in Fig. 5b for the profile elevation. The mean was subtracted out from the data before the analysis, implying that the modes associated with the dissipation can attain negative values. It is difficult to give physical interpretations to the mode shapes; however, the modes associated with the profile elevation reflects the presence of longshore bars at Duck, as discussed before. These modes are similar in shape to the lowest spatial EOFs obtained in the pre-processing step (compare Fig. 2a).

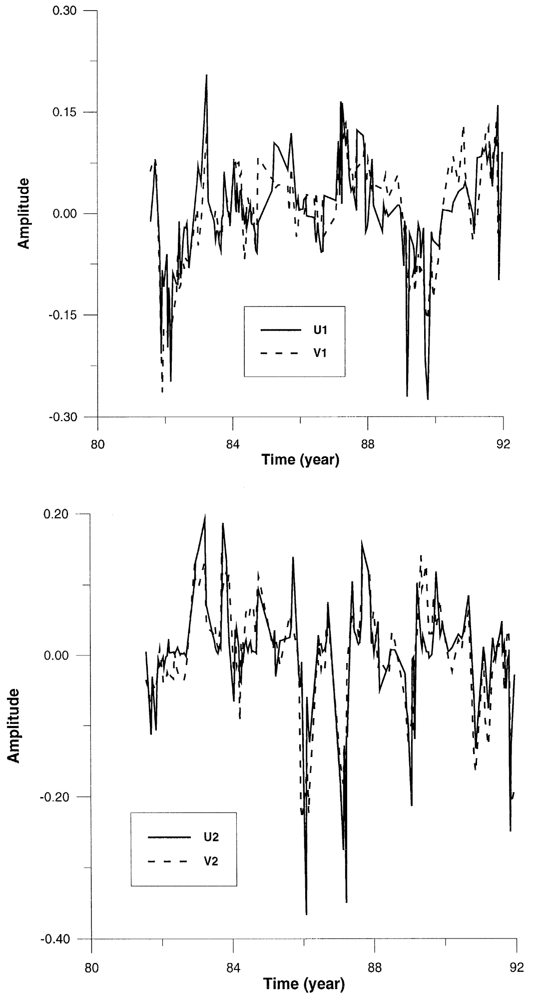

Fig. 4. Results of CCA analysis between mean wave energy dissipation and beach profile shape: (a) temporal amplitudes of the first CCA modes ($\mathbf{U}_1$ and $\mathbf{V}_1$) and (b) temporal amplitudes of the second CCA modes ($\mathbf{U}_2$ and $\mathbf{V}_2$).

The profile elevation was also correlated with the mean ratio of breaking waves determined at corresponding cross-shore locations. This analysis resulted in somewhat higher r-values with 0.80, 0.76, and 0.60 for the temporal amplitudes of the first three modes. Fig. 6a and b show the temporal amplitudes of the first and second modes, respectively, for the profile elevation and breaking wave ratio, whereas Fig. 7a and b display the spatial amplitudes of the first three modes for breaking wave ratio and profile elevation, respectively. The spatial amplitudes of the first mode for the breaking wave ratio show that more wave breaking close to shore is associated with more material in the profile here. Thus, higher waves with more wave breaking in the offshore implies that more material is typically found in the outer part of the profile. Analysis of profile elevation and rms wave height produced correlation values similar to the analysis between elevation and ratio of breaking waves.

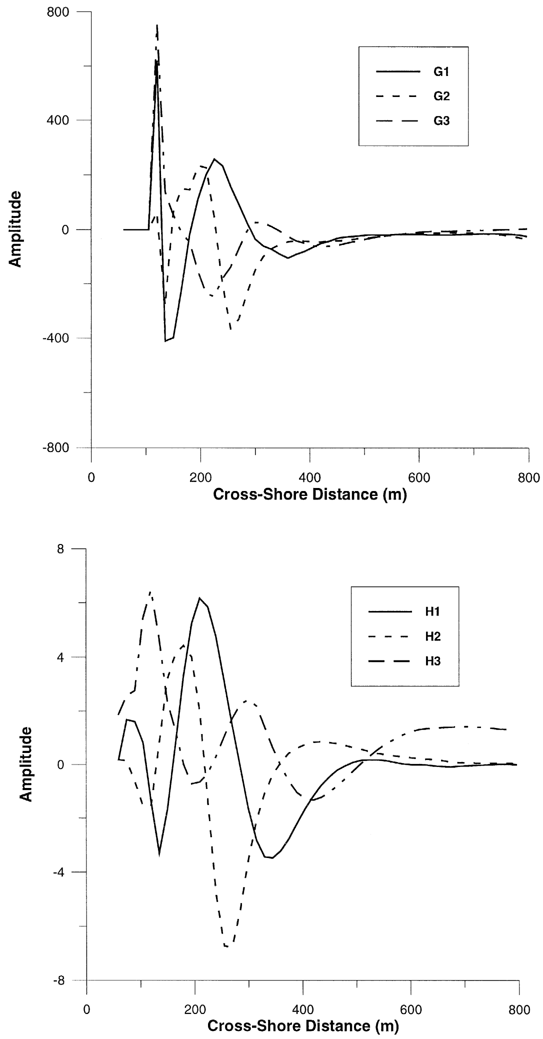

Fig. 5. Results of CCA analysis between mean wave energy dissipation and beach profile shape: (a) spatial amplitudes of the first three CCA modes for mean wave energy dissipation ($G_1 - G_3$) and (b) spatial amplitudes of the first three CCA modes for beach profile shape ($H_1 - H_3$).

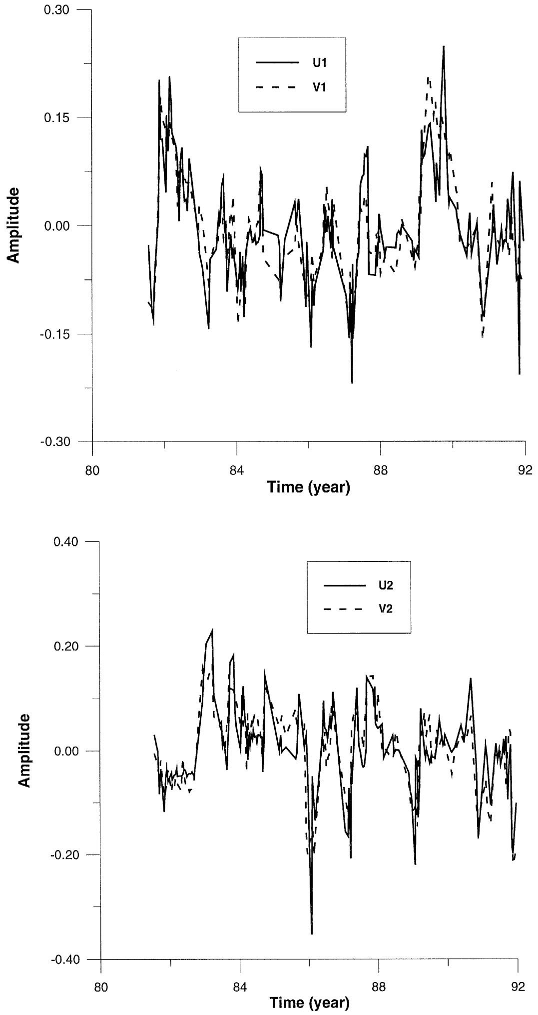

Fig. 6. Results of CCA analysis between mean ratio of breaking waves and beach profile shape: (a) temporal amplitudes of the first CCA modes ($\mathbf{U}_1$ and $\mathbf{V}_1$) and (b) temporal amplitudes of the second CCA modes ($\mathbf{U}_2$ and $\mathbf{V}_2$).

As an alternative to correlating profile shape and wave properties, the change in elevation between consecutive surveys was analyzed together with the local waves. The elevation change rate was determined by taking the difference between two consecutive profiles and dividing by the time elapsed between the profiles. In a statistical predictive model of elevation change, it may be more appealing to forecast elevation change than the profile shape itself, since it is physically more justified to relate change to the forcing, introducing some dynamics into the model, than to the shape itself. The elevation change rate, however, displayed somewhat less correlation with the wave properties than what the elevation did, especially for the higher modes. Correlating the elevation change with the mean energy dissipation, for example, gave an r of 0.65, 0.53, and 0.40 for the temporal amplitudes of the three first modes, to be compared with the values given above (0.77, 0.74, and 0.65).

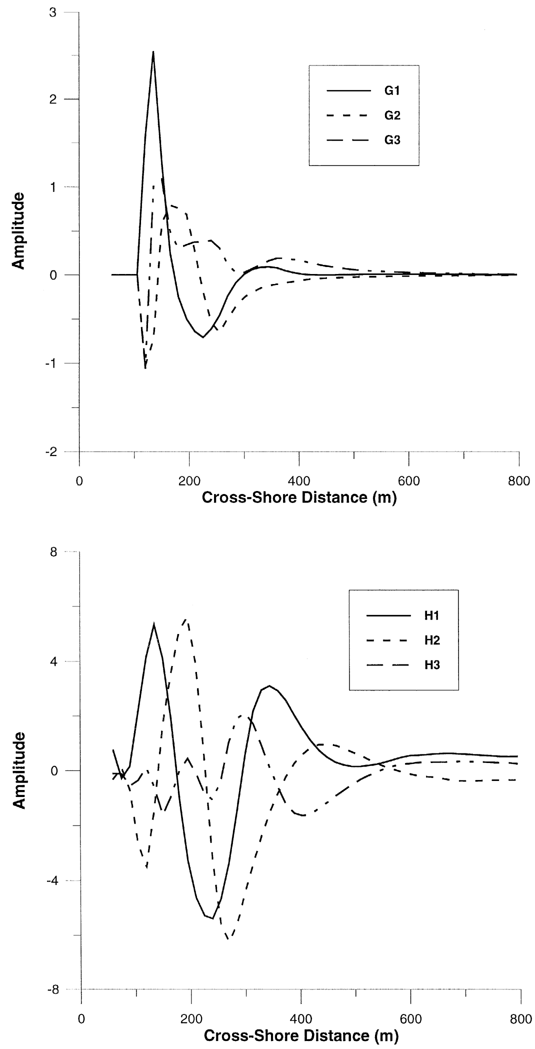

Fig. 7. Results of CCA analysis between mean ratio of breaking waves and beach profile shape: (a) spatial amplitudes of the first three CCA modes for mean ratio of breaking waves ($G_1 - G_3$) and (b) spatial amplitudes of the first three CCA modes for beach profile shape ($H_1 - H_3$).

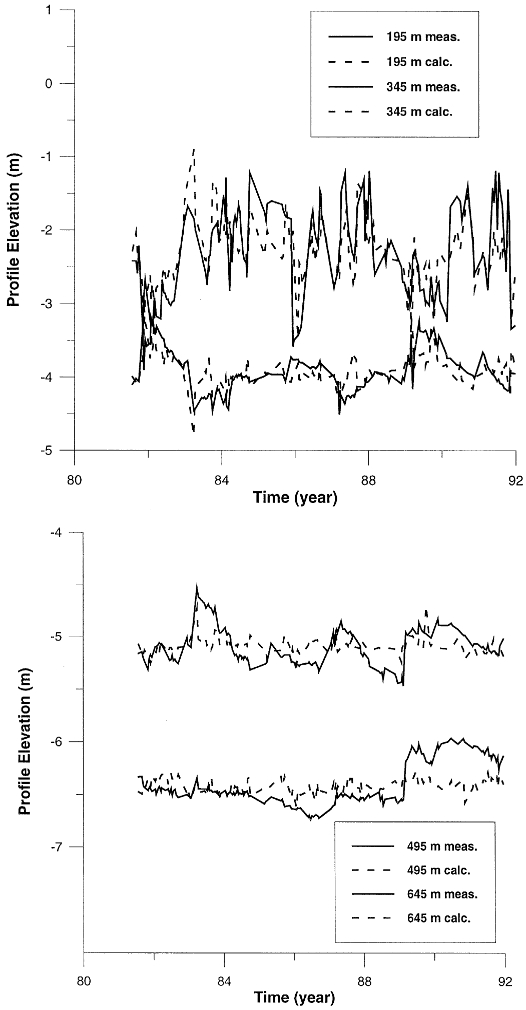

Fig. 8. Measured and calculated profile elevation at (a) cross-shore locations 195 and 345 m, and (b) at locations 495 and 645 m (distances given in the local coordinate system).

In order to further investigate the predictive capability of CCA, regression matrices derived from the data sets on profiles and waves were used to reconstruct the time series of profiles using a limited number of CCA modes. Here, some results from the analysis of profile elevation and breaking wave ratio will be discussed. To calculate the profiles, 10 CCA modes were employed. Fig. 8a and b display predicted and measured time series of elevation at selected cross-shore locations. Satisfactory agreement is achieved in the area where the profile exhibits considerable change, whereas in the offshore the discrepancy is relatively larger. The wave properties selected for the CCA are mainly related to wave breaking, which means that areas where this process dominates the sediment transport and profile response, such as in the nearshore, show better correlation. Tests were also made where the data series were split up and the first part was used to establish the regression matrix (Eq. (3)) and the second part to validate the predictive capability of the CCA model. The agreement between predictions and measurements for the validation part of the profile time series was less good than if the entire time series were used to derive the regression matrix. However, the difference was not too significant in the region where wave breaking is expected to be the predominant mechanism for profile change (i.e., where the largest changes occurred).

As a total measure of how well the profiles could be predicted from the breaking wave ratio using the regression matrix obtained from the CCA, the mean square deviation between predicted and measured profile elevation was calculated across the profile for all surveys (see Fig. 9). Also, the total variation in the data was quantified by computing the squared deviation between the measured profiles and the mean of the profiles at the same locations. The difference between the two curves in Fig. 9 indicates

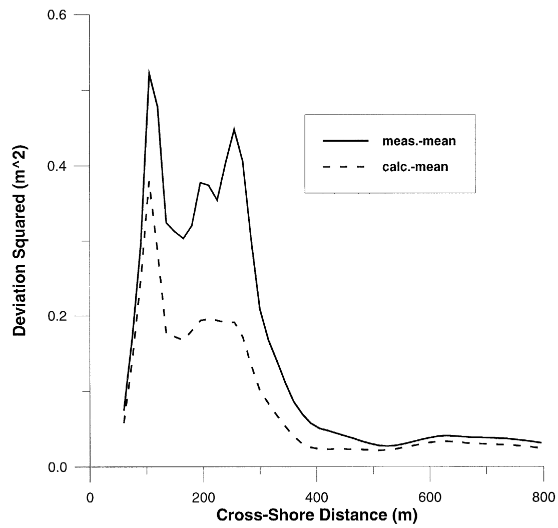

Fig. 9. Deviation squared between calculated and measured profile elevations together with deviation squared between measured profile elevation and the mean of the profile elevation.

how much of the variation that is explained by the CCA model. Thus, the model is explaining a large part of the variation (around 50%) in the nearshore out to about 400 m, but further offshore is the predictive capability more limited. This portion of the profile approximately encompasses the region where the longshore bars occur. Again, the nearshore wave quantities employed in this study were more or less related to wave breaking and it is not expected that the profile response in the offshore is well predicted by these quantities. This fact is reflected in the low percentage of explained variation observed in the seaward part of the profile (see Fig. 9). Another factor that contributes to the difficulties in predicting offshore profile response is the large vertical shift that occurred in this area during a sequence of storms in 1987 and 1989 (Capobianco et al., 1997).

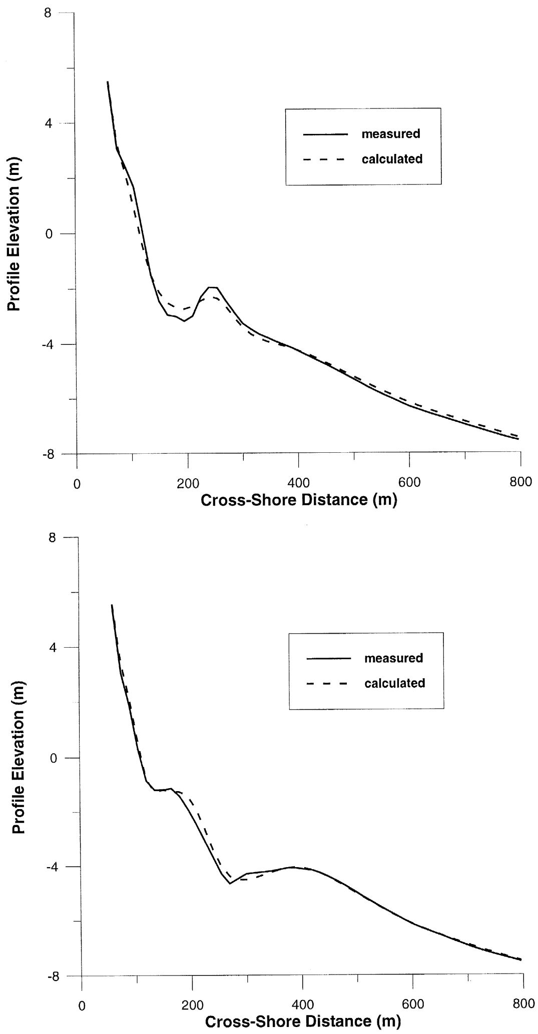

Fig. 10. Measured and calculated profiles at Duck for (above) a single-bar case (date 83/11/07) and (below) a double-bar case (date 86/03/11).

Fig. 10 illustrates two typical examples of how calculated and measured profiles compare, where the first case shows a single-bar profile and the second case a multiple-bar profile (the mean profile was added to the calculations with the CCA model). Both these measured profiles display significant deviations from the mean profile, which is close to exhibiting monotonically increasing depths with distance offshore. In the areas where the longshore bars occur on the average, the mean profile is almost horizontal (see Larson and Kraus, 1994). Although the predictions occasionally showed larger deviations than what Fig. 10 indicates, the results are fairly representative. The main difficulties for the regression model was to reproduce the vertical shift in the offshore that took place during the latter part of the study period, as mentioned earlier.

7. Concluding remarks

Selecting methods for analyzing and modeling long-term morphological evolution is intimately connected to the availability and quality of the data under study. In general, a more sophisticated method needs a larger amount of data as well as special requirements regarding the data sampling (e.g., at even intervals in time and space). Unfortunately, in the practical case, long-term morphological data is often scarce and restricted to a few variables, so that more advanced methods might be unsuitable or not possible to apply (note that the problem is often the inverse in geophysical applications, that is, such large amounts of data are available that advanced statistical methods are used for data reduction purposes to identify dominant patterns in the data). However, one such sophisticated method that could be applied with a relative modest amount of data is CCA. If a strong correlation is observed between two data fields (e.g., waves and profile change), CCA is an effective way of developing a predictive model and the need for data from each individual field might not be much larger than for traditional EOF analysis.

The results of the present study indicated that linear statistical analysis techniques based on data processing, such as CCA, are useful for analyzing profile response to waves. Used in conjunction with EOF technique to reduce noise in the data, CCA was found to be well suited for detecting concurrent variations in the wave and profile data. In addition, when used in a predictive mode, the CCA showed potential for forecasting profile response using nearshore wave properties. Calculated and measured profiles displayed quite good agreement for single-barred as well as multi-barred profiles. When used with offshore waves only, however, the correlation was not significant enough to suggest any direct predictive capability. However, it should be noted that the correlation between the temporal amplitudes of the CCA modes of offshore waves and profiles is high enough to indicate the existence of a well-defined cause-and-effect relationship. Although, this relationship cannot be fully resolved by a static model of the type used here, it could very well be described by a low-dimensional state-space model (i.e., a model that would not include any or little of the process dynamics).

The potential value of CCA application to forecast profile evolution should also be based on a careful examination of the stationarity and transferability of the regression matrix, i.e., the sensitivity of the matrix to the addition of new data, and the dependency of the matrix to the site. Some expert judgement should be used to assess the value of CCA applications with respect to possible modifications of the wave climate and to morphological differences in time and space.

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