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Wind Wave Attenuation over Saltmarsh Surfaces: Preliminary Results from Norfolk, England

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ABSTRACT

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An array of three bottom-mounted pressure transducers (placed approximately 200 metres apart along a shore-normal transect centred on the sandflat/saltmarsh transition) was used to measure changes in wave characteristics across sandflat and saltmarsh on the Norfolk coast, UK. Pressure readings were taken at a frequency of 5Hz over periods of 5 and 7 minutes at different times during the tidal cycle over a range of tides between September 1994 and May 1995. The time-series were corrected to offset attenuation with depth of the high frequency fluctuations. A comparison of surface waves computed in this way with observations made using a video camera showed a significant positive correlation. Analysis of all 54 records showed a consistent energy decrease of between 47.4% and effectively 100% across the saltmarsh section of the transect. This differed significantly from the much lower wave energy reduction (1.9 to 55.3%) across the sandflat section of the transect. Reduction in wave energy and significant wave heights was only weakly related to water depth across the sandflat, but more strongly related to water depth across the saltmarsh. The results suggest that saltmarshes are extremely effective in buffering wave energy over the range of water depths and incident wave energies investigated here. The increased surface roughness of saltmarshes is likely to be most effective in reducing wave energy at low to intermediate water depths or during conditions of high incident waves.

ADDITIONAL INDEX WORDS: *Coastal defence, wave energy, wave recording, marsh surface hydrodynamics.*

INTRODUCTION

A large proportion of European saltmarshes (approximately 38%; DIJKEMA, 1987) are exposed to significant incident energy from wind-generated waves. Recent monitoring of intertidal profiles on foreland coasts with extensive mudflats and more landward saltmarshes suggests that they can be usefully viewed as a low-energy analogue of beach profile adjustment to varying nearshore energy conditions (PETHICK, 1992). This energy-buffering function, and its manifestation in the reduction of wave heights across marsh surfaces, has engineering significance since it permits the relaxation of design criteria for flood defence embankments where these are fronted by saltmarsh (BRAMPTON, 1992). Concern over near-future accelerated sea level rise and the potential costs of raising and strengthening existing lines of coastal defence has stimulated interest in mechanisms by which mudflat and saltmarsh surfaces dissipate wave energy and the efficiency with which they do so. Better understanding of the physical effect of saltmarshes upon wave hydrodynamics is necessary in order to (i) inform policies of 'coastal setback' (or 'managed retreat'), where an expanded intertidal zone is created between existing and newly constructed landward defences (BURD, 1995); and (ii) provide design criteria for the restoration of degraded marsh systems or the creation of new protective marshes in front of threatened defences.

Scale physical model experiments undertaken in the UK during the 1980s suggest a wave height reduction of approximately 40% over an 80 m wide saltmarsh from shoaling and breaking processes and from frictional losses (BRAMPTON, 1992) but these results were not validated by complementary field observations. There have been remarkably few such studies. WAYNE'S (1976) work on a Florida saltmarsh indicates a substantial reduction of wave height and total energy (71% and 92%, respectively) over a 20 m transect, although it is difficult to reconstruct the methods and tidal sampling strategy employed. KNUTSON *et al.* (1982) reported similarly large reductions within the marshes of Chesapeake Bay; virtually all the incident wind-wave energy was removed at the end of a 30 m transect. Both these studies were conducted in densely vegetated stands of tall *Spartina alterniflora* (cordgrass), under very low incident wave energies. We know of no comparable published work on wave energy transformations within European locations subject to a storm wave climate. This paper reports preliminary findings on the modification of wave characteristics across a sandflat to saltmarsh transect on the marshland coast of eastern England over a range of tidal flooding events.

STUDY LOCATION

The North Norfolk coast of eastern England is an area of extensive backbarrier and open coast saltmarshes which have developed behind offshore bars, spits, or shallow sloping sandflats. Local isostatic subsidence and eustatic sea level rise appear to contribute roughly equally to a relative sea

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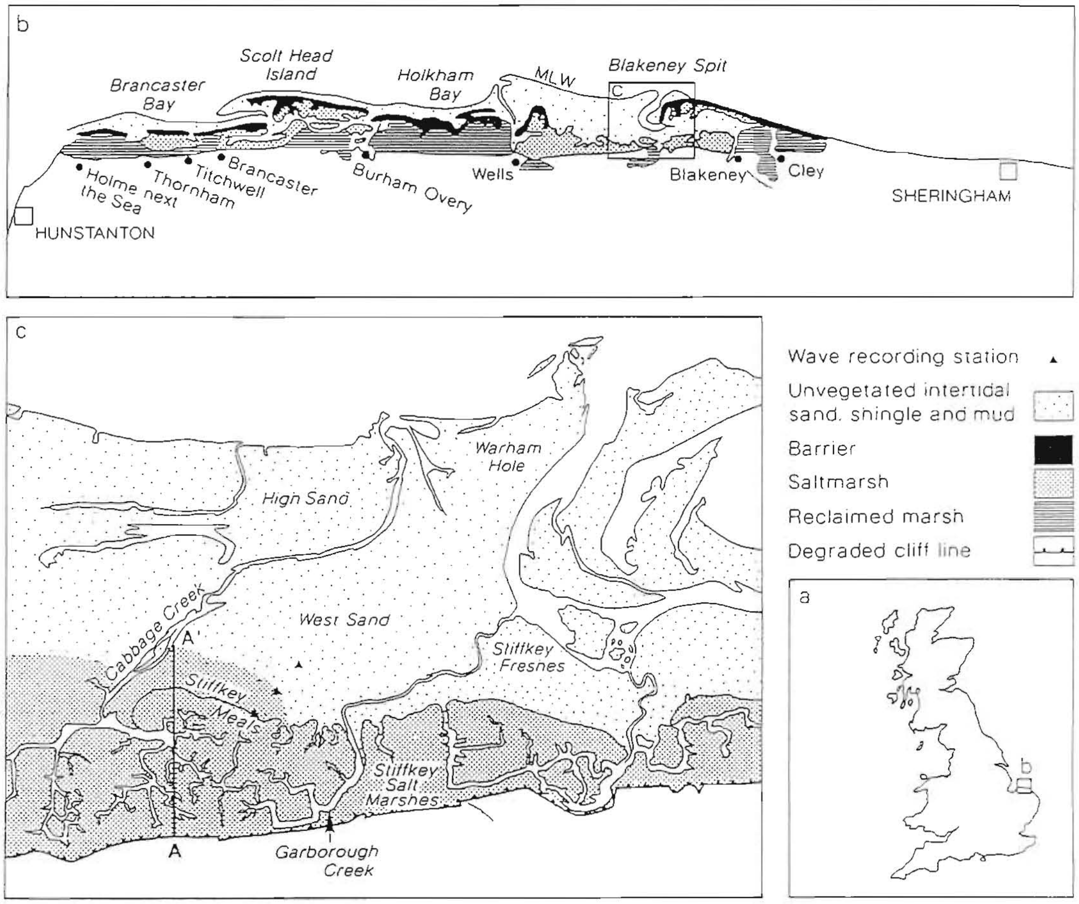

Figure 1. Location and coastal environments. a: North Norfolk coast, eastern England; b: Intertidal, barrier and back-barrier environments (after Spencer and French, 1992); c: Stiffkey Marshes (source: 1:25,000 Ordnance Survey map, 1984) with location of wave recording stations (△). For section A-A′ see Figure 2.

level rise of just under 2 mm yr^{-1} (FRENCH, 1993). The coast is just macrotidal with a semi-diurnal regime; mean spring tidal range varies from 6.6 m at Hunstanton in the west to 4.7 m in the east at Cromer (HYDROGRAPHER TO THE NAVY, 1994). The southern North Sea is, however, susceptible to storm surges which can raise water levels considerably above predicted tidal levels, and at times well in excess of the Highest Astronomical Tide. Water levels reached 4.91 m and 5.13 m above Ordnance Datum (O.D. ≈ mean sea-level) at Wells Quay in the storm surges of 1978 and 1953 respectively (STEERS *et al.*, 1979).

The field site for this study was at Stiffkey (Figure 1). These marshes are exposed to the northeast, the direction of greatest fetch from the North Sea, but are locally sheltered by an 1.5–2.0 km-wide belt of intertidal sand flats characterised by well developed migratory bars. The marshes are 800–1,000 m wide and divided into two types by a low shingle ridge (approximately 3.2 to 4.0 m above O.D.). The 'high' marsh landward of the ridge reaches 2.8 m O.D.; the 'low' marsh fronting the ridge varies in height from 2.8 m O.D. just seaward of the barrier to 2.5 m O.D. at its seaward margin (Figure 2). Marsh sediments are predominantly clastic (silt/clay with variable sand inclusion), with organic contents of <15% by weight (FRENCH and SPENCER, 1993). Air photo evidence (see also PETHICK, 1980) suggests that the present 'low' marsh developed in the 1950s to 1960s but has been eroding since the late 1970s; the seaward margin is degraded into a hummocky topography, drained by poorly defined anastamosing channels.

The 'high' marsh is dissected by networks of incised creeks and typified by a floristically-diverse 'General Saltmarsh Community' (including species such as *Suaeda maritima, Puccinellia maritima, Halimione portulacoides, Armeria maritima, Aster tripolium, Limonium vulgare*) which is typical of east coast UK marshes (ADAM, 1978) whereas the more hummocky 'low' marsh is dominated by a pioneer community of *Salicornia* spp., *Spartina anglica, Limonium vulgare, Aster tripolium* and clumps of *Halimione portulacoides*. The vegetation 'roughness elements' are thus more complex than the thin stems of tall *Spartina alterniflora* stands studied by WAYNE (1976) and KNUTSON *et al.* (1982). Aboveground biomass is lower in the saltmarshes of eastern England compared with North American *Spartina* marshes. Also, the lower growth habitats mean that the saltmarsh vegetation may be completely inundated at Stiffkey during the higher spring tides. The attenuation of wave energy might therefore be expected to exhibit some de-

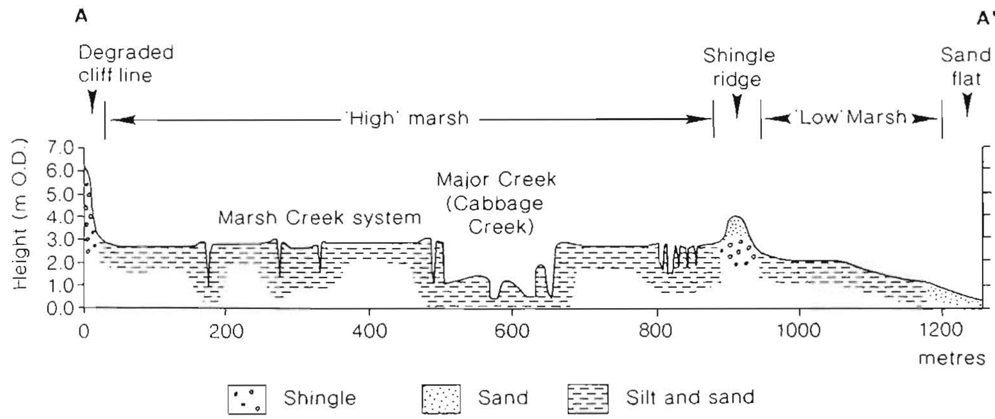

Figure 2. Generalized cross-section through the Stiffkey marshes. For location see Figure 1.

pendence on mean water level, as well as on the width of saltmarsh and the incident wave energy.

METHODS

Sampling Design

Information on wave periods, wave heights and mean water level was obtained at three locations along a transect (orientated 44.5° from N) from the shingle ridge across the 'low' marsh and the sandflat at Stiffkey (Figure 1). The middle wave recording station was located on the 'low' marsh at the marsh/sandflat transition, 197 m landward of the outermost recording station on the tidal flat. The distance between the middle station and the inner station just seaward of the shingle ridge was 180 m. The sandflat between the outer and the middle station is unvegetated and characterised by small scale bedforms developed in response to tidal currents and waves. The 'low' marsh between the middle and the inner station is dominated by a linear ridge/mud mound topography. Data were collected over a range of spring tides between September 1994 and May 1995.

Wave Recording and Signal Processing

Wave measurements utilised a 'Druck' pressure transducer (series PDCR380) mounted 5 to 10 cm above the sandflat or

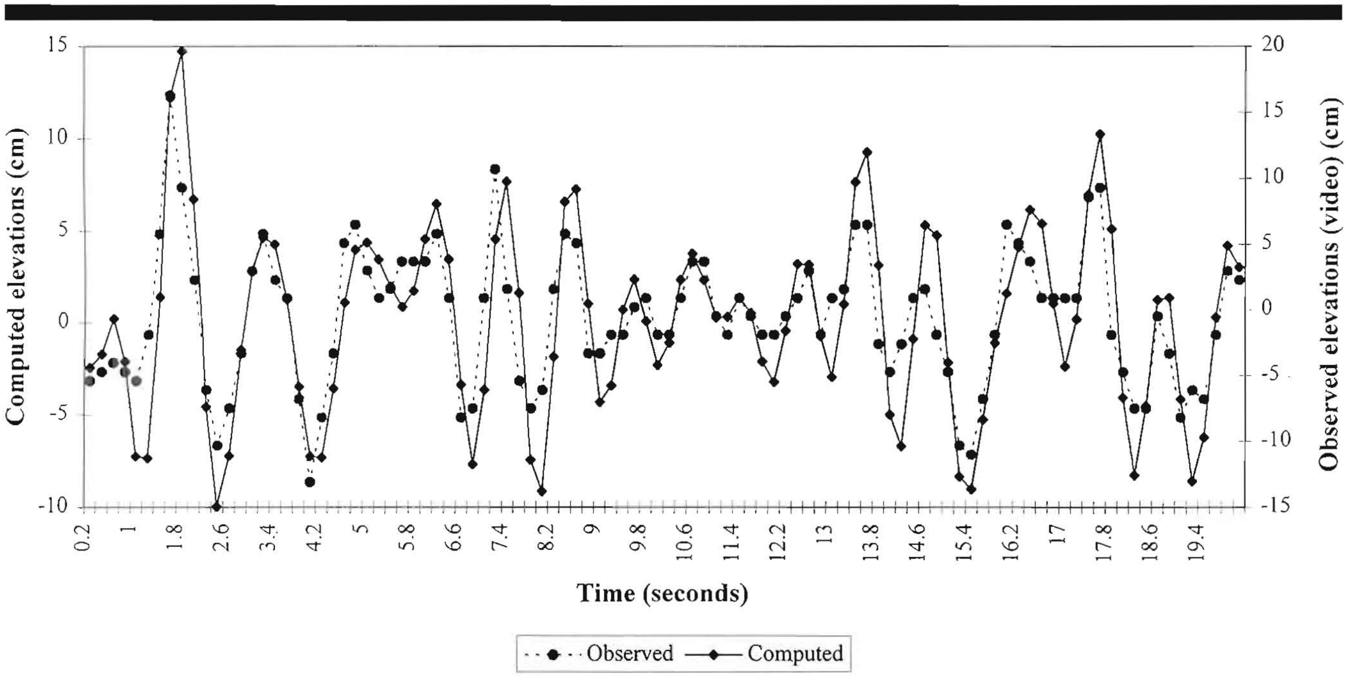

Figure 3. Comparison of water surface elevations calculated from pressure readings and water surface elevations recorded by calibrated video.

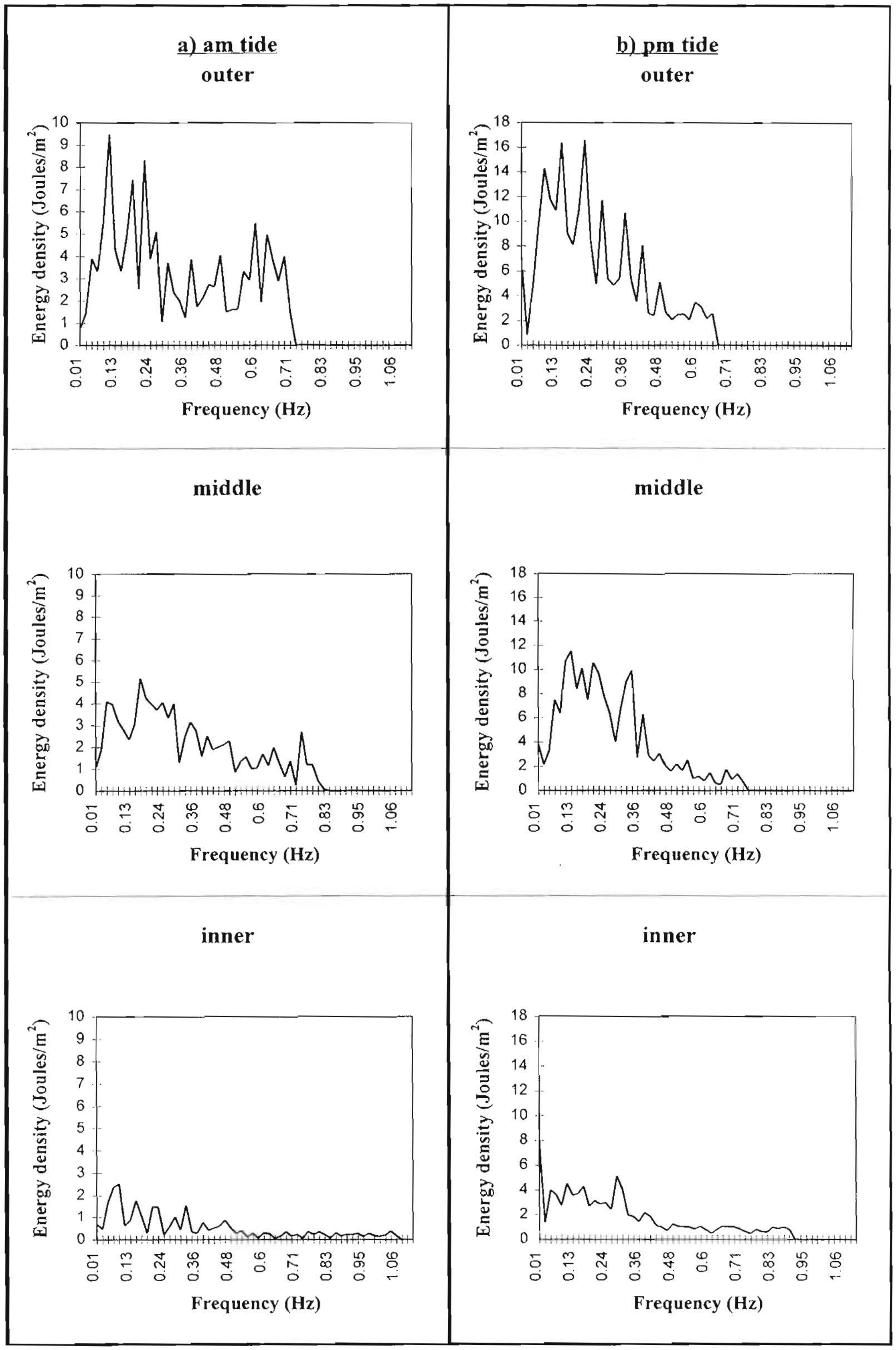

Figure 4. Comparison of wave spectra at the three measurement stations for two specimen tides (morning (a) and evening (b) of 19 March 1995). Timing is 20 minutes after high water; mean water depth is 1.48 m (a) and 1.75 m (b) at outer station. Spectra are smoothed by averaging over 8 Fourier frequency intervals.

Table 1. *Summary wave characteristics for 54 'burst' spectra, September 1994–March 1995.*

	E_{tot} (Joules/m²)			Change in E_{tot} (%)		
	outer	middle	inner	outer-mid.	mid.-inner	outer-inner
Maximum	277.09	196.41	91.21	−55.27	−99.98	−99.99
Minimum	5.16	5.07	0.00	10.86	−47.36	−49.21
Mean	70.72	49.52	12.87	−26.34	−79.64	−83.80
Median	51.38	34.03	3.59	−27.06	−82.39	−86.98
	H_s (m)			Change in H_s (%)		
	outer	middle	inner	outer-mid	mid.-inner	outer-inner
Maximum	0.67	0.56	0.38	−33.10	−98.37	−99.15
Minimum	0.09	0.09	0.00	5.25	−27.45	−28.72
Mean	0.30	0.25	0.11	−14.65	−58.33	−63.53
Median	0.29	0.23	0.08	−14.59	−58.02	−63.92
	H_{rms} (m)			Change in H_{rms} (%)		
	outer	middle	inner	outer-mid.	mid.-inner	outer-inner
Maximum	0.47	0.40	0.27	−33.09	−98.75	−99.16
Minimum	0.06	0.06	0.00	5.30	−27.46	−28.77
Mean	0.21	0.18	0.08	−13.45	−53.60	−63.54
Median	0.20	0.16	0.05	−14.58	−58.06	−63.94
	T_z (seconds)			T_z shift (seconds)		
	outer	middle	inner	outer-mid.	mid.-inner	outer-inner
Maximum	4.27	3.86	7.88	−1.32	4.82	4.46
Minimum	1.57	1.35	0.74	0.29	−1.86	−2.25
Mean	2.92	2.74	2.79	−0.18	0.05	−0.14
Median	3.00	2.66	2.80	−0.16	−0.04	−0.24

saltmarsh surface. Analog transducer output was digitised and stored in a datalogger ('Campbell Scientific 21X') which was mounted on top of a 3 to 5 m high metal framework ('Dexion') tower. Towers were located 2 to 3 m landward of the sensor so as to prevent interference of the structure with approaching waves. The time required to take an individual pressure reading and the storage capacity of the dataloggers (approximately 5,700 readings) limited the duration of wave recording over an individual tidal cycle to 19 minutes, using a sampling frequency of 5Hz. To obtain information on wave conditions at different stages of the tidal cycle, the 19 minutes available were divided into two 7-minute and one 5-minute record. The three records were collected either (a) at the time of predicted high tide on three consecutive tides or, more usually, (b) on individual tides 20 to 30 minutes before high water, at high water, and 20 to 30 minutes after high water. A total of 54 complete wave pressure records were obtained between September 1994 and May 1995.

Processing of the electronic transducer signal time series can be divided into three stages:

(i) Linear de-trending to remove low frequency tidal components.

(ii) Application of a frequency-dependent correction to the raw pressure fluctuations to offset the attenuation with depth of the high frequency end of the wave spectrum. This used the assumptions of linear wave theory (CERC, 1984) and was accomplished via a Fast Fourier Transform (FFT) based algorithm (TUCKER, 1991).

(iii) Calculation of summary wave parameters from the corrected free surface record and its frequency spectrum ($S(f_n)\Delta f$) (see TUCKER, 1991); these included the zero-upcrossing wave period (T_z), spectral peak period (T_p), significant and root-mean-square wave heights (H_s and H_{rms}), and the total wave energy (E_{tot}) in Joules m^{-2}:

$$S(f_n)\Delta f = 0.5a_n^2$$

$$E_{tot} = \sum_{n=1}^{N} S(f_n)\Delta f g\rho = \sum_{n=1}^{N} 0.5a_n^2 g\rho$$

$$H_S = 4\sqrt{E_{tot}\frac{1}{g\rho}}$$

$$H_{rms} = 2\sqrt{2}\sqrt{E_{tot}\frac{1}{g\rho}}$$

where:

$S(f_n)$ = the energy density in the n^{th} component of the spectrum
Δf = frequency bandwidth of the spectrum
a_n = amplitudes of the component waves of the spectrum
N = total number of measurements (time series length)
g = gravitational acceleration
ρ = water density (1.02 g cm^{-3})

Validation of Wave Records

Although linear wave theory is strictly applicable only in deep water, the equations are usually considered a reasonable approximation for shallow water conditions (CERC, 1984). However, there are also practical difficulties associated with the recovery of surface wave information from corrected subsurface pressure measurements, with linear transfer functions of the type employed here tending to slightly underestimate the energy in the lower frequency range, whilst overestimating the higher frequency contributions (see, for example, LEE and WANG, 1984). To establish whether surface waves computed from near-bed pressure records corresponded to actual water surface fluctuations, a video camera was used on a selected tide to record water level fluctuations visually at a frequency of 25 frames per second against a calibrated staff. The directly observed free surface record was then compared with that computed from simultaneous near-bed pressure measurements. Figure 3 shows a portion of the observed and calculated free-surface record for 22 September 1994 at the middle station. Statistical analysis of the two time series showed a correlation coefficient, r, of 0.85 (statistically significant at the 95% confidence level ($p = 0.05$)).

RESULTS

Figure 4 (a and b) shows typical contrasts in wave frequency spectra along the transect of three measuring stations on the morning and the evening tide of 19 March 1995, when the mean water depth at the outer station was 1.48 m and 1.75 m (the highest in any of the records) respectively. These data show two characteristics common to the majority of com-

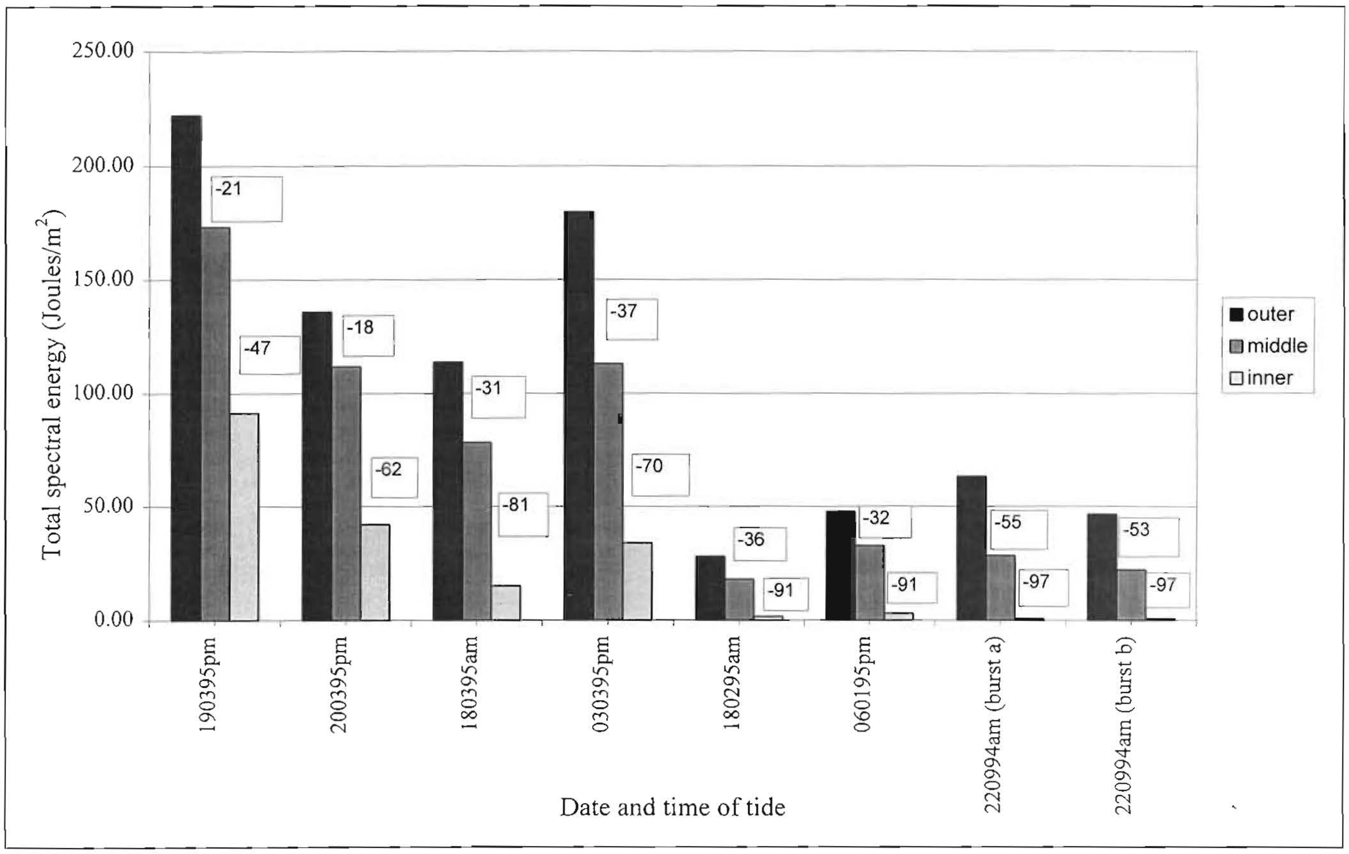

Figure 5. Total energy reduction between outer, middle and inner stations for a sub-sample of 8 tides (percentage reduction between outer and middle station shown in upper boxes; percentage reduction between middle and inner station shown in lower boxes adjacent to bars).

puted wave spectra: (i) a slight decrease in both total energy and the energy of the dominant waves between the outer and the middle station (*i.e.* across the sandflat); and (ii) a sharp reduction in total energy from the middle to the inner station (*i.e.* across the saltmarsh).

Summary statistics of the 54 wave records collected between September 1994 and May 1995 are given in Table 1. Most records were collected within half an hour of high water. Mean water depths during individual records varied from 0.91 m to 1.75 m at the outer station and from 0.52 m to 1.39 m at the inner station. Total spectral energy calculated from the height spectra decreased by between 1.9% and 55.3% across the sandflat between the outer and middle stations (although a small energy increase was observed in three records). There was a consistent energy decrease between the middle and inner stations during all 54 records varying from 47.4% to effectively 100%.

Figure 5 illustrates the changes in total spectral energy across the sandflat and the saltmarsh for a sample of 8 tides. Although total wave energy was expected to vary with water depth (as deeper water allowed greater transmission of wave energy across the tidal flat), the statistical relationship between these variables was very weak ($r = 0.33$). More significantly, perhaps, the reduction in wave energy and H_s was only weakly related to water depth across the sandflat ($r = -0.46$ and -0.47 for wave energy and H_s respectively), but more strongly related to water depth across the saltmarsh section ($r = -0.73$ and -0.79) of the transect.

There was no significant relationship between T_p and water depth; the two extreme periods of 1.34 s and 13.65 s at the outer station were in fact measured on very similar water depths (1.11 m and 1.46 m respectively). As expected, T_z varied much less than T_p at all stations. Minimum and maximum T_z were 1.57 s and 4.27 s, 1.35 s and 3.86 s, and 0.74 s and 7.88 s at the outer, middle, and inner stations, respectively. Mean T_z were very similar at the outer, middle, and inner stations (2.92 s, 2.74 s, 2.79 s, respectively).

Wave properties between adjacent stations for all 54 wave records were tested for statistical significance (t-tests (paired, two-tailed) at $p = 0.05$). Mean total spectral energy loss

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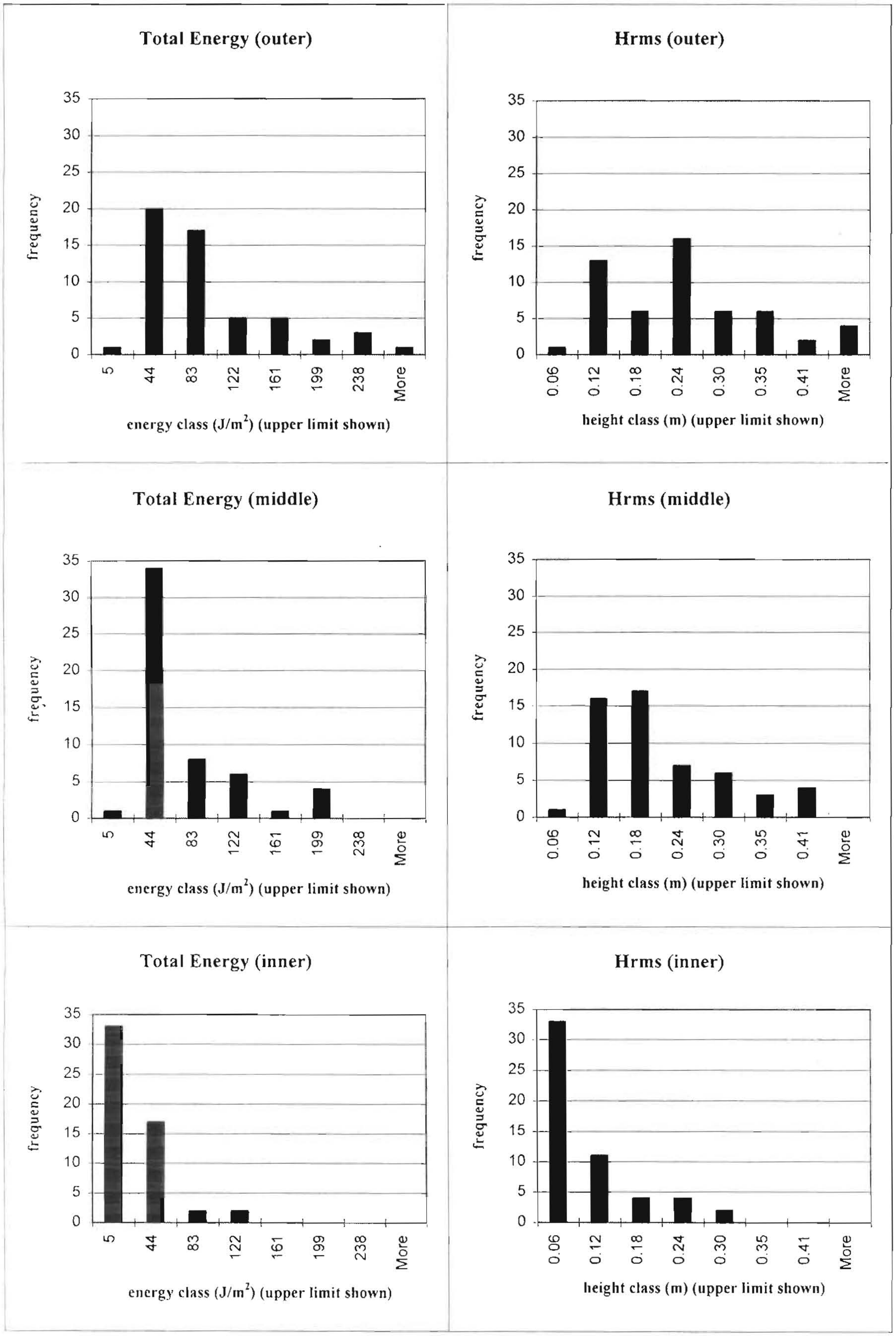
Figure 6. Frequency distribution of H_{rms} and H_s for the wave records obtained at each of the three measurement stations.


Total Energy (outer)
frequency
35
30
25
20
15
10
5
0
5
44
83
122
161
199
238
More
energy class (J/m²) (upper limit shown)
Hrms (outer)
frequency
0.06
0.12
0.18
0.24
0.30
0.35
0.41
More
height class (m) (upper limit shown)
Total Energy (middle)
frequency
energy class (J/m²) (upper limit shown)
Hrms (middle)
frequency
height class (m) (upper limit shown)
Total Energy (inner)
frequency
energy class (J/m²) (upper limit shown)
Hrms (inner)
frequency
height class (m) (upper limit shown)

across the sandflat (approximately 26%) differed significantly from that across the saltmarsh (approximately 79%). The reduction in H_s across the sandflat (mean reduction 13.5%) differed significantly from that across the saltmarsh (53.6%). H_{rms} reduction across the sandflat (14.6%) also differed significantly from that across the saltmarsh (58.3%). Frequency histograms of these height parameters are given in Figure 6.

CONCLUSIONS

The dataset reported here represents the first comprehensive quantitative investigation of wind wave attenuation over a European saltmarsh. A relatively low-cost data acquisition system proved reliable in all conditions and, with careful post-processing of the raw pressure series, yielded a good correspondence between calculated and independently observed surface wave parameters.

Large reductions in both wave height parameters and total wave energy occur across the instrumented intertidal profile. The wide tidal flat at Stiffkey is clearly important in reducing the wave energy incident upon the marsh edge, and measurable attenuation of wave energy occurred even over the upper 200 m of the flat. The rate of energy and height attenuation with distance is much higher over the vegetated marsh, however. Because of the different transect lengths studied, it is difficult to make direct comparisons with the previous field observations in *Spartina alterniflora* marshes (WAYNE, 1976; KNUTSON *et al.*, 1982) and laboratory model experiments (BRAMPTON, 1992). The mean wave energy loss of 80% over the 180 m marsh surface transect, whilst substantial, clearly implies a lower rate of attenuation than that observed in *Spartina alterniflora* marshes. Comparison with the scale model experiments referred to by BRAMPTON (1992) is complicated by the relative large deepwater wave heights simulated (H_s = 1.75 m, compared to the maximum H_s of 0.67 m observed at the outer tidal flat station at Stiffkey).

Further work is needed to examine the changing rate of wave modification with distance landwards across the saltmarsh surface, and additional data are required under higher incident wave energies in order to derive a more usable set of design criteria for the incorporation of saltmarshes into sea defence works. The increased surface roughness characteristic of saltmarshes is likely to be most effective in attenuating waves at low to intermediate water depths or during conditions of high incident waves (*i.e.* high wave height to water depth ratios). This view is supported in this study by the more significant negative correlation between water depth and wave attenuation across the saltmarsh than across the sandflat. Further analysis of the presented dataset (including meteorological conditions and information on marsh vegetation) will be carried out to establish the importance of small differences in marsh surface elevation. In contrast to marsh surface elevation, the width of the marsh may be far more important in determining the effectiveness of a saltmarsh in buffering wave energy.

It is now important to extend these studies to other field locations, and to acquire a larger dataset that allows more experimental control over the relative effects of marsh width, height, vegetation characteristics, and incident wave energy.

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