Wave dissipation over macro-tidal saltmarshes: Effects of marsh edge typology and vegetation change

Authors: Möller, I., and Spencer, T.

Source: Journal of Coastal Research, 36(sp1) : 506-521

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/1551-5036-36.sp1.506

Journal of Coastal Research	SI 36	506-521	(ICS 2002 Proceedings)	Northern Ireland	ISSN 0749-0208

Wave dissipation over macro-tidal saltmarshes: Effects of marsh edge typology and vegetation change

I. Möller and T. Spencer

Cambridge Coastal Research Unit,
Department of Geography, University of Cambridge,
Downing Place, Cambridge CB2 3EN,
UK

ABSTRACT

To achieve sustainable coastal management and planning, the interaction between fine-grained - in particular, vegetated - intertidal environments and incoming waves needs to be better understood. Previous studies have established that wave attenuation over saltmarshes can be significantly greater than over unvegetated intertidal surfaces. However, detailed, quantitative information on the effect of marsh elevation in the tidal frame, marsh width, seaward marsh edge configuration (e.g. cliffed versus ramped marshes), seasonal changes in marsh surface roughness (e.g. creek density, vegetation composition) and incident wave conditions, however, has been lacking.
Based on a 10-month-long wave/tide dataset from two sites on the Dengie marshes, eastern England, this study addresses the effect of (i) marsh edge topography; (ii) marsh width; (iii) inundation depths; and (iv) seasonal changes in marsh surface vegetation cover on wave height and wave energy dissipation. Directional waves and water levels were recorded at 21 locations across both shallow-sloping and cliffed (cliff height of ca. 1.5m) intertidal profiles. In addition, changes in marsh surface vegetation cover and composition were recorded on a seasonal basis.
Wave height attenuation over 310m of the shallow-sloping profile averaged 92 % over the monitoring period. Further analysis shows that the most rapid reduction in wave heights occurs over the most seaward 10 meters of permanent saltmarsh vegetation, where wave height attenuation averaged 2.1% and 1.1% per meter at the shallow-sloping and cliffed site respectively. Across the mudflat and the saltmarsh as a whole, wave height dissipation rates were significantly lower with an average of 0.1% and 0.5% per meter respectively. The presence of a saltmarsh cliff increased average wave heights by up to 0.5% per meter. Observed wave height attenuation showed a seasonal pattern at both sites (average wave energy attenuation near the marsh edge was highest in September – November and lowest in March – July) and appears to be linked to the cycle of seasonal vegetation growth.
The study provides criteria for the assessment of the wave dissipation potential of marshes characterised by different widths, edge configurations and slopes, variability of water depths, and seasonal variations in vegetation cover/density.

ADDITIONALINDEXWORDS: *wave attenuation, coastal management, intertidal hydrodynamics, coastal geomorphology*

INTRODUCTION

Coastal wetlands have high conservation and resource value (COSTANZA *et al*. 1997), sustain the productivity of estuarine and open coast ecosystems (MITSCH and GOSSELINK 1993) and are important nutrient sinks (TWILLEY *et al*., 1992). Both directly and indirectly, they aid the maintenance of large, and often rapidly growing, human populations in coastal hinterlands. Considerable areal losses of intertidal mudflats and saltmarshes have been taking place, however, in both the developed (e.g. Mississippi delta: DAY *et a*l., 2000) and developing world (e.g. SE Asia: EDINGER and BROWNE 2000) as a result of land use change; altered hydrodynamics and sediment supply; and the prevention of landward habitat migration by fixed sea defence lines. Not only are these processes themselves of considerable concern but they are likely to be augmented by further wetland loss from near-future accelerated sea level rise (e.g. NICHOLLS *et al*., 1999). At the same time, coastal wetlands are an important component in attempts to re-formulate coastal defence and shoreline management policy towards more sustainable outcomes (TITUS 1991, DIXON *et al*., 1998). Efforts to maintain existing wetlands, to restore degraded marshes and to create new, artificial marshes requires theoretical, methodological and practical developments in ecological engineering which will need to be based on a better understanding of the natural morphodynamics of fine-grained, intertidal, vegetated environments (FRENCH and REED 2001).

The rapidity with which natural wetland extent can change is due to the fact that saltmarshes in the upper intertidal zone exist in a delicate balance between a state characterised by vertical accretion and infilling of the tidal frame, healthy vegetation growth and lateral progradation and one described by surface degradation and landward retreat. Numerical modelling studies have suggested that the key controls on this dynamic, acting singly or in combination, are changes in tidal regime and wind-wave climate, relative sea level change, sediment supply and vegetation and soil-forming processes (e.g. ALLEN 1990, FRENCH 1993). This balance is sufficiently sensitive for rates of both marsh progradation and marsh retreat to be rapid (of the order of meters per year (e.g. PRINGLE 1995) and for historical cycles of advance and retreat to be recorded in the changing planform and sedimentary record of saltmarsh systems (e.g. CARPENTER and PYE 1996; ALLEN and RAE 1988).

A particularly key set of process-form linkages are those between surface elevation, vegetation cover, hydrodynamics and sedimentation. Once established above a critical height in the tidal frame, well-vegetated saltmarsh surfaces are highly efficient dissipators of wind-wave and tidal energy. Recent studies by the authors (MOELLER *et al*., 1996, MÖLLER *et al*., 1999) have shown incident wave energy reduced by an average of 82% over a pioneer saltmarsh on the meso-tidal North Norfolk coast, eastern England, compared to only 29% energy reduction over a comparable width of fronting sandflat. Application of a one-dimensional model (MÖLLER *et al*., 1999) has demonstrated that the enhanced dissipation over the saltmarsh is due to the additional friction associated with the presence of a vegetation cover. These findings complement laboratory (SHI *et al*., 1995) and field (STUMPF 1983, Wang *et al*., 1993, LEONARD *et al*., 1995, SHI *et al*., 2000) studies within marsh vegetation canopies which have shown the extraction of tidal momentum by plant ‘roughness elements’.

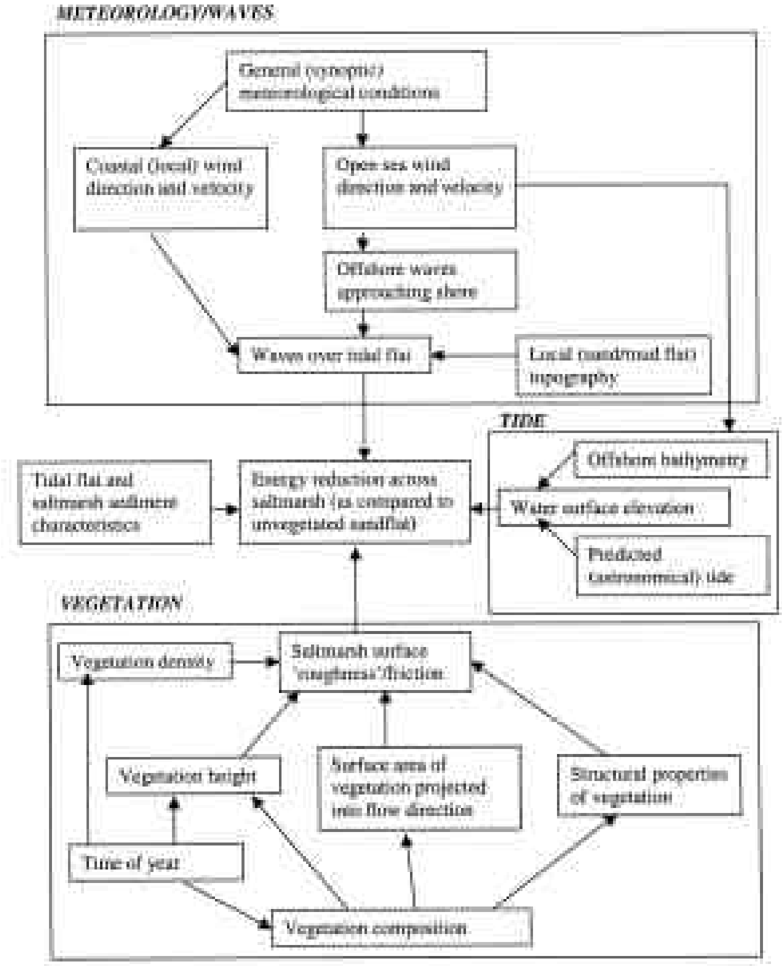

Figure 1. Factors influencing wave energy dissipation over saltmarshes

There is a general supposition that even a narrow fringe of fronting saltmarsh is effective in reducing wave energy at the base of sea defence structures (FRENCH and REED 2001). In Chesapeake Bay, KNUTSON *et al*., (1982) demonstrated a 50% reduction in wave energy within 2.5m of the marsh edge but here incident wave heights were very low (< 0.2m) and the vegetation canopy, of closely packed, tall stems of cordgrass, *Spartina alterniflora*, quite different from the low, floristically diverse 'General Saltmarsh Community' (ADAM, 1978) of eastern England. Physical modelling studies (BRAMPTON 1992) suggest that most of the overall reduction in wave heights over a typical North West European saltmarsh surface occurs within the first few tens of metres of the seaward marsh edge but this has not been verified by field observations. In addition, it appears that an important, but as yet unquantified, contributory factor to the degree of wave attenuation experienced comes from the nature of the mudflat / saltmarsh transition.

As in other systems where there are strong form - process - vegetation linkages (e.g. sand dunes: JUNGERIUS and Van der MEULEN 1988), there are process thresholds at which energy dissipation by a vegetative canopy is overcome and vegetation loss and morphological change take place. Such changes may be temporary, such as in the flattening and then recovery of saltmarsh margins after individual storm events (e.g. PETHICK 1992). However, in systems dominated by erosion a marked cliff may develop at the transition between unvegetated mudflats and vegetated saltmarsh surfaces (e.g. JACOBSEN 1980, Van EERDT 1985, ALLEN 1989). These marsh edge topographies then impact upon the wave energy dissipation that takes place during events of lower magnitude and greater frequency.

Landward of the marsh edge, wave energy dissipation is affected by marsh surface micro-topography, including the presence / absence of salt pans and surface - dissecting creek systems, and the nature of the vegetation cover. Numerical modelling studies have made some progress in assessing vegetative roughness in terms of the combined effects of element diameter and element spacing (e.g. DALRYMPLE *et al*., 1984, KOBAYASHI *et al*., 1993). It has proved difficult, however, to quantify vegetation roughness effects in the field, partly because of the difficulty in assessing plant mechanical properties, such as rigidity and buoyancy, and partly because of the difficulty in defining meaningful community-level vegetative growth forms and structural arrangements. Furthermore, these characteristics change both temporally over the course of the growing season at any particular location on the marsh surface and spatially across the marsh at any point in time, as is well demonstrated by repeat remote sensing of patterns of marsh surface primary productivity (SMITH *et al*., 1998).

Thus, the extent to which incident wave energy is dissipated by saltmarshes results from a combination of the factors of edge configuration and marsh surface roughness (*sensu lato*), allied to prevailing hydrodynamic conditions (including incident wave characteristics, direction of wave approach relative to the marsh edge and water depth) and their variability over time (Figure 1). The primary aim of this paper is to establish, in more detail than has hitherto been demonstrated, patterns of spatial and temporal variability in wave energy dissipation over mudflats and landward saltmarshes on a macro-tidal storm-dominated coast, with a recent history of saltmarsh retreat. In particular, this study i) assesses the role of marsh edge topography in determining the nature of wave attenuation; ii) compares wave energy dissipation at the marsh edge with attenuation in marsh interiors; and iii) establishes seasonal variations in wave energy dissipation and determines to what degree these differences may be assigned to seasonal changes in plant growth forms and vegetation cover characteristics.

Study Area

The estuarine coast of Essex, England, forms the northern boundary of the Thames estuary system in the southern North Sea. In this study, field monitoring was undertaken on the Dengie Peninsula between the estuaries of the Rivers Blackwater and Crouch (Figure 2). The eastern, and particularly south eastern, Peninsula consists of former marshland of Holocene age (GREENSMITH and TUCKER 1973), progressively reclaimed up until ca. 1875 (GRAMOLT 1960). This area is comprehensively enclosed by earth embankments and some concrete revetments and concrete walls, typical of the sea defences of the Essex coast (DIXON *et al*., 1998). The defences are fronted by active saltmarshes of varying width but reaching up to 700m wide in the centre of the Peninsula. The intertidal flats extend seaward for up to 4 km from the marshes before giving way to a complex topography of NE - SWtrending flood and ebb tidal channels and intervening sandbanks which dry at low tide.

Map and chart evidence suggests that the present marshes formed rapidly between 1870 and 1950, and particularly after 1891 - 95. Between 1955 and 1973 mean progradation rates of 9.7m a^{-1} characterised central Dengie although these rates were not matched at either the northern or southern extremities of the Peninsula (PYE and French 1993). GREENSMITH and TUCKER (1965) reported marsh edge retreat of up to 270m between 1953 and 1960 in the northern half of the Peninsula. Between 1960 and 1981, the entire marsh frontage underwent net recession, albeit with considerable temporal and spatial variability (HARMSWORTH and LONG 1986). The maximum recorded retreat was in the central sections where ca. 1000m of marsh was lost between 1955 and 1985 at Howe Outfall

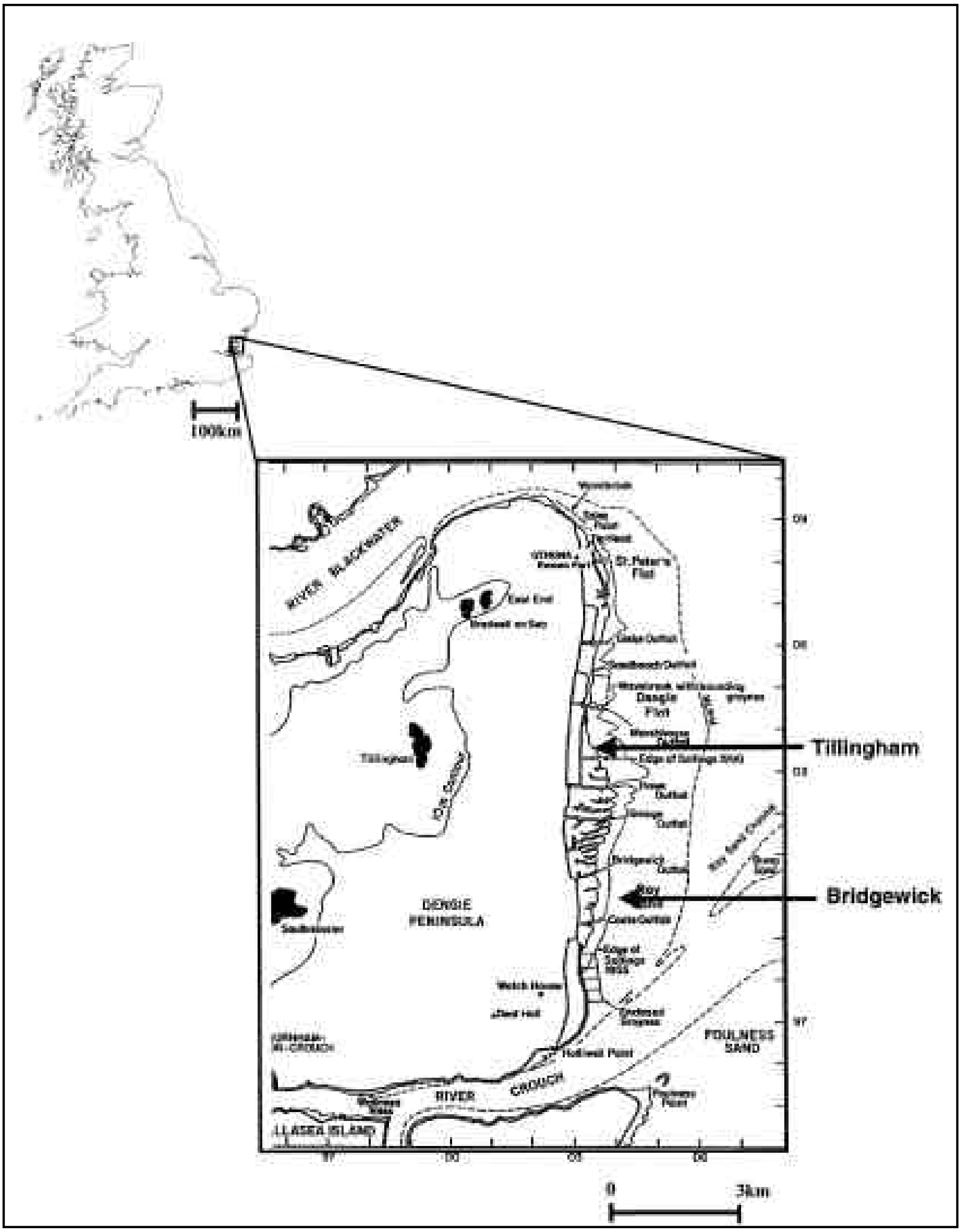

Figure 2. Location of study area (after Pye and French 1993) and the two field monitoring sites

(PYE and FRENCH 1993). In 1980, 'sedimentation fields' were constructed in the south at Deal Hall (PETHICK and REED 1987) and this was followed by the placement of sunken barges to form wavebreakers at Marsh House (1984) and Sales Point (1986). These measures appear to have raised foreshore levels and stabilised the shoreline (CARPENTER and PYE 1996). Bi-annual monitoring of cross shore profiles since 1991 (Figure 3) also indicates a slowing of erosion rates in the recent past.

Tidal flats immediately to seaward of the marshes are typically at elevations of 0.9 - 1.4m above Ordnance Datum Newlyn (ODN; approximates to mean sea level). They are composed of sands and silty sands (PYE and FRENCH 1993) and typically organised into a 'mudmound topography,' of shore-normal sinuous ridges and runnels, thought to be characteristic of an eroding coast (GREENSMITH and TUCKER 1975). Marsh surfaces are composed of clayey silts and are approximately horizontal, with elevations of between 1.9 to 2.2m (PYE and FRENCH 1993) or 2.4 - 2.5m ODN (REED 1988) (Figure 3). The vegetation is typical of floristically diverse east coast saltmarshes of the British Isles (ADAM 1978) and is dominated by *Aster, Suaeda, Puccinellia, Salicornia,* and *Limonium* spp. Three types of marsh - mudflat transition are found on the Dengie Peninsula. At Sales Point and near Marsh House, the marsh edge is characterised by shell mounds and washover fans, termed 'chenier ridges' by GREENSMITH and TUCKER (1975). The second margin type is a low-angle ramp where the creeks which dissect the marsh surface lead into the larger runnels in the mudmound topography. Thirdly, the marsh edge may be a cliff, varying in height from 1.5 to 2.2 m; the contact with the mudflat may be distinct or the cliff front may be stepped from the presence of mud blocks in the process of being detached from the cliff face. The latter two transition zone typologies were considered in this study.

The Dengie Peninsula coast is macrotidal, with a mean spring tidal range of 4.8 m, although this range is reduced at the marsh edge (REED 1988). HUTHNANCE (1991) has estimated the offshore 50 year return period significant wave height ($H_s(50)$) as 8.0m. Hindcast offshore wave data from meteorological records for Long Sand Head (42 km NE) yield a mean annual wave height of 1.09m (1994 - 96), with winter (January) mean monthly maxima of 1.45 - 1.70m (HERMAN 1999). In shallow water environments, however, these heights are much reduced, with a maximum recorded significant wave height of 0.65 m, and a predicted $H_s(50)$ of 0.78 m, at Sales Point on the northern limit of the Peninsula (HERMAN 1999; sensor at -2.2m ODN). The southern North Sea is particularly susceptible to storm surges. In the last century, the severe storm surges of 1949, 1953 and 1978 raised water levels up to 1.92, 2.40 and 1.60m respectively above predicted tidal levels (STEERS *et al*., 1979). Numerical models predict a 50 year return period storm surge of + 2.5m for the Essex coast (FLATHER 1987). In a worst case scenario of the combination of the annual Hs maximum with the 50 year return period maximum tidal level (SWL(50)), HERMAN (1999) predicted water depths of 6.84m ODN at Sales Point; would lead to water depths of over 4.5m over marsh surfaces and an overtopping of the sea defences by 1.8m. Current rates of sea level rise for the Dengie Peninsula have been estimated at 2 - 3 mm a^{-1} (PYE and FRENCH 1993).

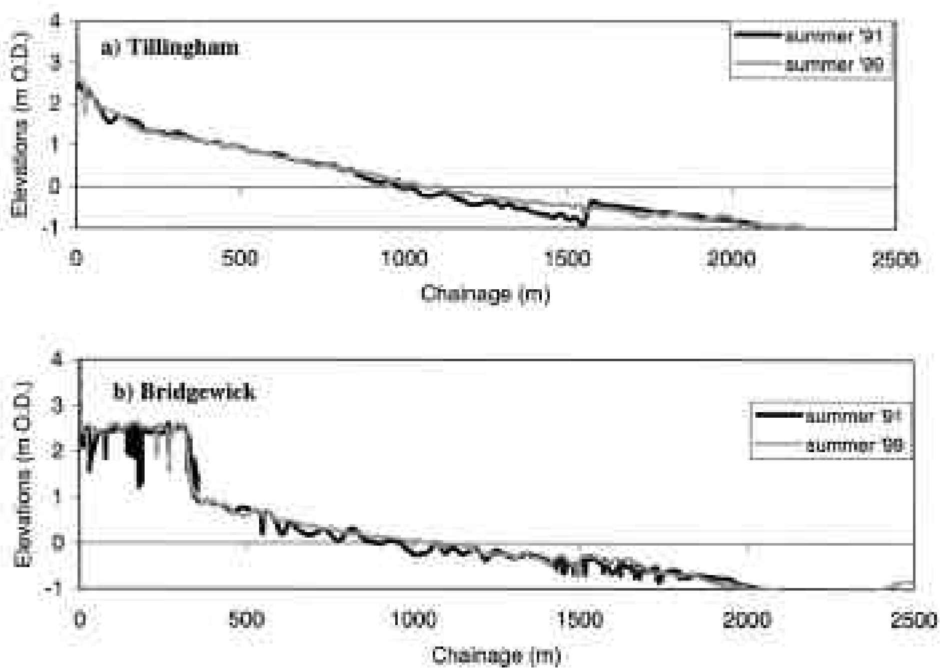

Figure 3. Shore-normal saltmarsh to mudflat profiles at a) Tillingham and b) Bridgewick, indicating morphological change 1991-99. Source: H Schans unpublished data, based on U.K. Environment Agency profiles

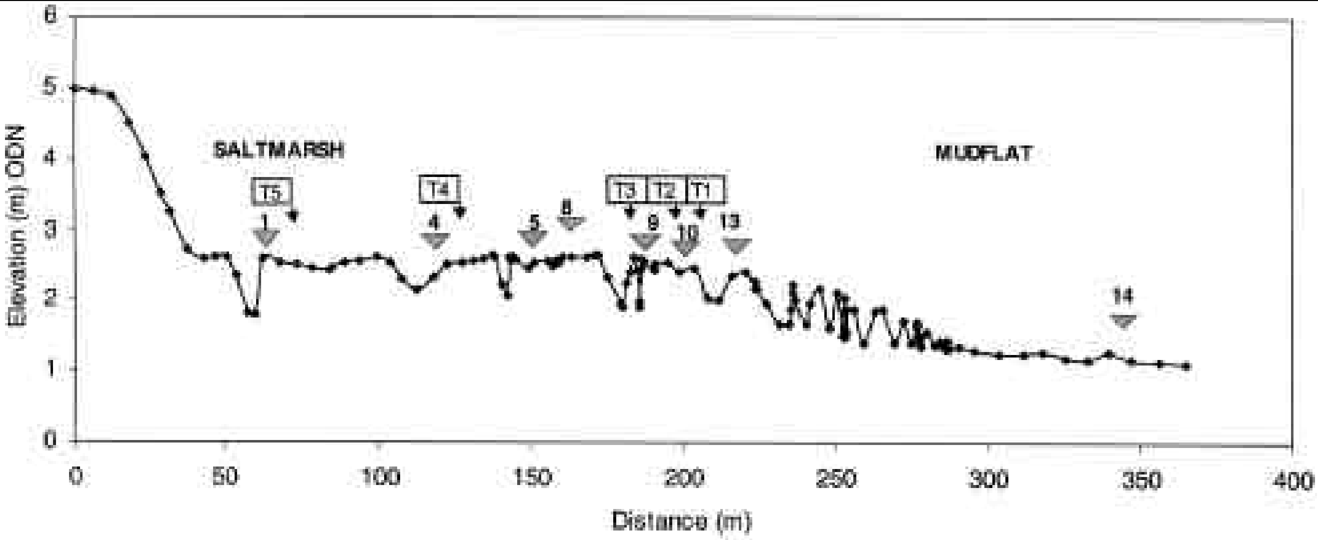

Figure 4. Shore-normal profile at Tillingham, showing the location of pressure sensors (numbered triangles) and vegetation measurement sites (T1-5)

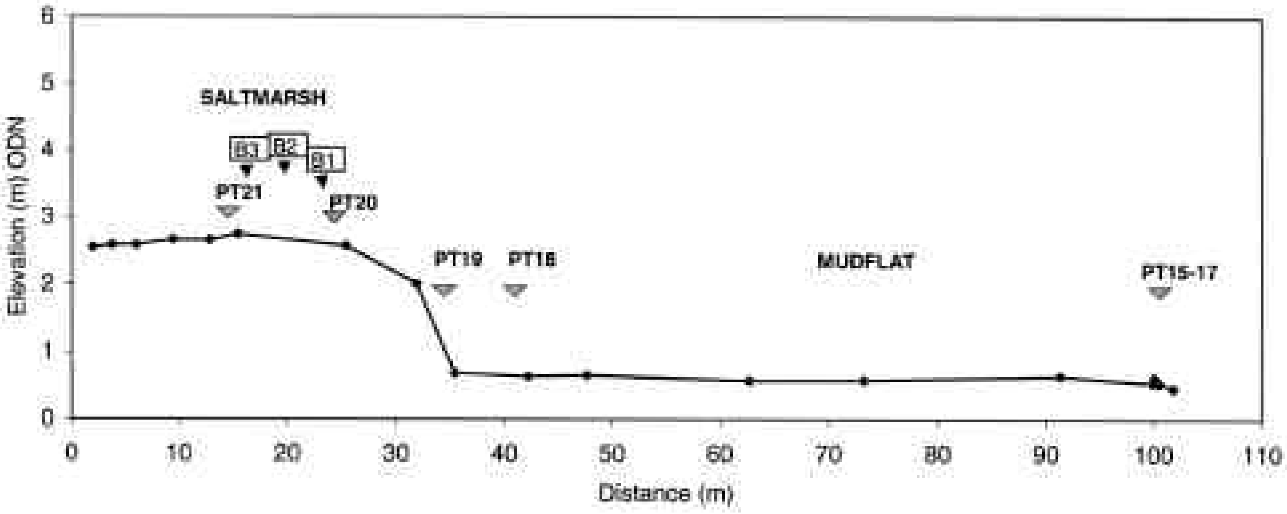

Figure 5. Shore-normal profile at Bridgewick, showing the location of pressure sensors (numbered triangles) and vegetation measurement sites (B1-3)

METHODS

Experimental design

Wave and water level data collection followed the methodology of MÖLLER *et al*., (1999) and involved the deployment of Druck 'PTX1830' pressure transmitters, orientated shore-normal 10 cm above the mudflat / saltmarsh surface and connected to Campbell Scientific 'CR10'dataloggers for data storage. X, y and z co-ordinates for all sensors were established by field survey to local benchmarks, with elevations being converted to ODN, at both the beginning and end of the monitoring period. Two marsh sites were monitored intensively (Figure 2). At Tillingham, 14 pressure sensors were deployed on a wide, 310m long transect from mudflat to saltmarsh, including a ramped transition zone (Figure 4). Pressure sensor layout was designed to provide the greatest spatial resolution in the area of seasonal vegetation at the seaward margin of the saltmarsh and in the first 10m of the transition from seasonal to annual vegetation cover on the marsh surface. At Bridgewick, the intertidal profile is characterised by an abrupt transition between unvegetated mudflat and vegetated saltmarsh in the form of a 1.5 - 2.0m high cliff (Figure 5). 7 pressure sensors were deployed on a 112m long transect at this location; layout was designed to provide greatest spatial resolution in the immediate vicinity of the marsh edge cliff (Figure 5). At the marsh edge at Tillingham, and at the most seaward mudflat position at Bridgewick, the pressure sensors were arranged in a small triangular array to enable the subsequent derivation of the angle of wave approach.

Wave/tide measurements

Water level and wave activity were recorded in one 30 minute burst per tidal inundation at a frequency of 4hz. Bursts were taken at high water when the flooding of the marsh surface is greatest and when the confounding effects of tidal currents are at their minimum. Control pressure sensors at both locations monitored water level rise on the flood tide every five minutes and triggered the commencement of the burst when water level change over this interval approached zero. This event-based methodology represents a significant improvement on earlier sampling designs which have relied upon pre-programmed (astronomically predicted) high water times. These often bear little resemblance to actual high water times, particularly during the stormier winter months. With less wasted data logger capacity, longer wave bursts were recorded, in turn leading to reduced error terms in computed spectral wave statistics (see below).

After calibration in August 2000, routine measurements were carried out over a 10 month period from September 2000 to July 2001 (although UK Government access restrictions due to Foot and Mouth Disease prevented some data recovery February - May 2001). Given their range of elevations, the number of occasions on which individual sensors were inundated varied considerably: thus the outer mudflat sensors at Bridgewick were inundated 228 times, but the marsh interior sensors at Tillingham only 39 times, during the study period. Due to (a) the small number of tides that inundated all sensors and (b) some initial loss of data as a result of data storage problems with the mudflat sensors, there were 19 occasions at Tillingham, and 23 at Bridgewick, when the entire sensor array was inundated simultaneously. Taking all individual sensors into account, however, 2929 records of water level variation were collected for subsequent analysis. Using the data from all pressure sensors, it was possible to construct a total of 236 and 279 tidal stage curves for the Tillingham and Bridgewick sites respectively.

Post-processing of waves and water level records

A standard depth adjustment procedure (MOELLER *et al*., 1996) was applied to all records. It has been shown in previous studies (e.g. MOELLER *et al*., 1996) that a water level record reconstructed in this way provides a true representation of actual water levels. A Fast Fourier Transform (FFT) algorithm was used to derive wave statistics, computational efficiency being optimised by editing wave bursts to a length of 212 (4096) values (i.e 1024 seconds). In addition to water depth at the commencement of the wave burst, the following statistical wave parameters were calculated for each burst as follows:

derived from the wave spectrum:

- Significant wave height (Hs)
- Peak period (Tp)
- Total wave energy contained in the wave spectrum (Etot)

derived from the depth-adjusted time-series of water level fluctuations:

- Zero-upcrossing-period (Tz)
- Maximum wave height (Hmax)

In addition, the direction of wave approach was determined, following Howell (1998), by computing the cross-spectra for the wave records from the triangular array of sensors at each location.

Vegetation mapping and analysis

Vegetation surveys were undertaken in November 2000 and February, June and September 2001 to establish seasonal changes in vegetation composition and community structure. Both vertical and horizontal colour photographs were taken at 5 locations at Tillingham (see Figure 4) and 3 locations at Bridgewick (Figure 5). While horizontal photographs were taken of a 10cm wide belt of vegetation in front of a white background, vertical photographs captured a 1m x 1m quadrat placed on the marsh surface.

The vertical photographs were analysed visually by dividing the quadrat into a grid of 100 sub-cells of equal size and determining the presence of different species in each of the cells. The sum of the squares in which a particular species was present was then taken as its percentage cover.

The horizontal photographs were analysed digitally using Erdas 'Imagine' image processing software to determine vegetation density and canopy structure. This was achieved by classifying image pixels into either a 'background' or a 'vegetation' class using an unsupervised classification algorithm. The subsequent computation of the ratio of vegetation to background pixels provides an estimate of the surface area of vegetation projected into the horizontal wave-driven current. As the field of view remained constant in all images, the variation in this ratio provides a relative measure of vegetation density variations between the different sample locations.

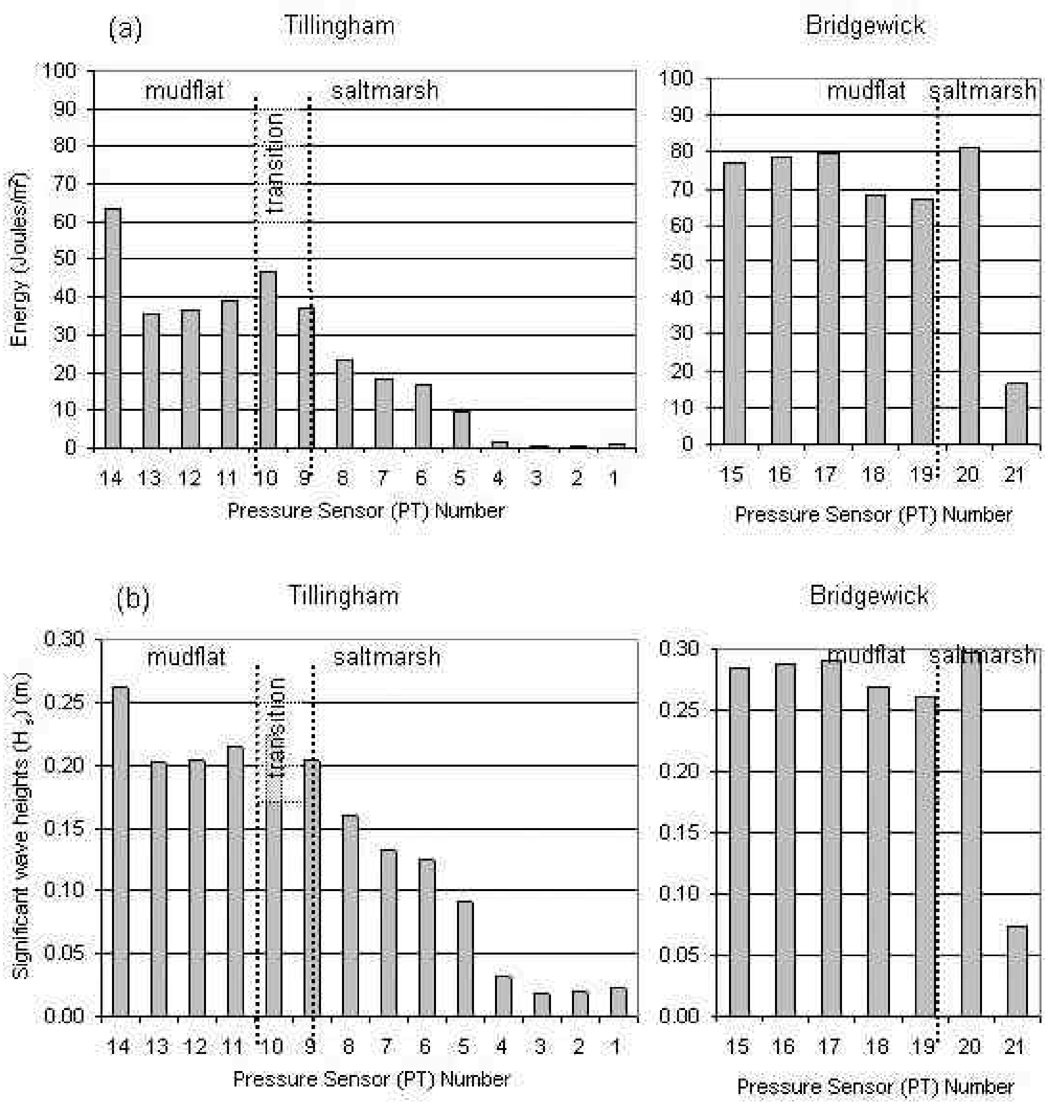

Figure 6. Mean values of (a) wave energy and (b) significant wave height at the pressure sensor locations at Tillingham and Bridgewick (for location of sensors, see Figure 4 and 5).

RESULTS

Tidal elevations and water depths

The vast majority of recorded tidal high waters at Tillingham (172 out of 236, i.e. 73%) reached elevations of between 2.5 and 3.0m ODN (mean of 2.7m ODN). At Bridgewick, the majority of recorded tidal high waters reached slightly lower elevations (162 out of 279 (i.e. 58%) between 2.0 and 2.5m ODN; mean of 2.1m ODN). Only very few of the water level records obtained (4 at Tillingham and 2 at Bridgewick) exceeded elevations of 3.25m ODN.

Over the mudflat (200m seaward of the marsh edge) at Tillingham, water depths thus ranged between 0.96 to 1.95m (with a mean of 1.41m), while depths ranged from 0.5 to 2.71m (with a mean of 1.84m) on the mudflat at Bridgewick, due to its lower surface elevation. Water depths ranged from 0.12 to 0.84m at the marsh edge at Tillingham (with a mean of 0.43m) and from 0.12 to 1.04m (with a mean of 0.33m) on the edge of the cliff top at Bridgewick. Ca. 20m landward from the marsh edge, water depths were comparable at Tillingham (0.27 to 0.68m) and Bridgewick (0.21 to 0.65m).

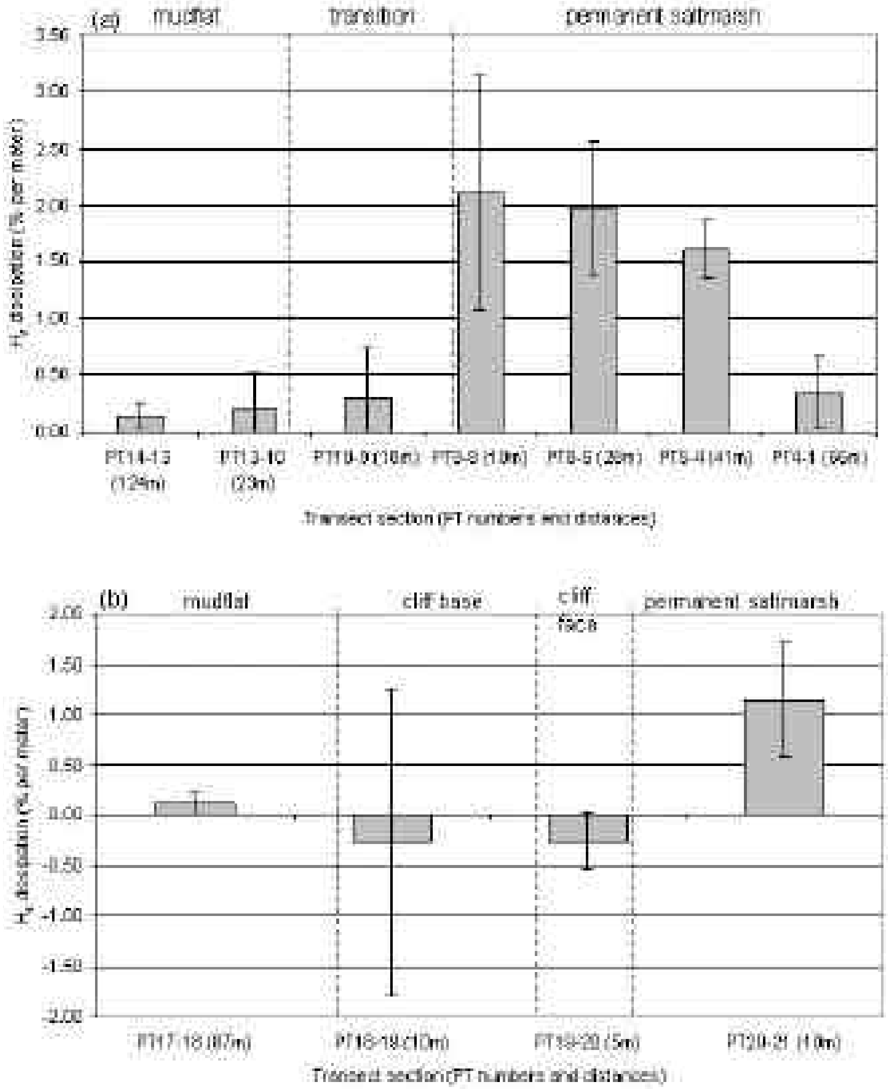

Figure 7. Mean significant wave height dissipation between individual sensors at (a) Tillingham and (b) Bridgewick (for sensor locations, see Figure 4 and 5)

Incident wave characteristics on the mudflat

The distribution of significant wave heights (Hs) on the outer mudflat was remarkably similar at Tillingham and Bridgewick with means of 0.26m and 0.29m respectively. The more extreme significant wave heights (up to 1.08m) were encountered at Bridgewick (significant wave heights never exceeded 0.86m at Tillingham). Figure 6 shows the mean significant wave heights and energy for all wave bursts at all measurement locations and along the central shore-normal transects at the two field sites. As expected from the differences in significant wave heights, the two field sites differed considerable with respect to the mean wave energy recorded on the mudflats (54.1 Joules/m^2 at Tillingham and 63.7 Joules/m^2 at Bridgewick). With respect to maximum energies observed, this difference was even more pronounced with 464.2 Joules/m^2 observed at Tillingham but 715.0 Joules/m^2 recorded at Bridgewick.

Zero-upcrossing periods on the mudflats were generally around 3s and comparable between the two measurement sites (means for Tillingham and Bridgewick of 2.64s and 2.82s, respectively).

While most records at Bridgewick were collected when wave approach was shore-normal, at Tillingham most records were collected when waves were approaching at oblique angles (from the northeast rather than the east).

Spatial patterns of wave energy dissipation across the mudflat – saltmarsh transects

Taking all those records collected when all sensors of the respective monitoring transect were inundated, significant wave height (Hs) attenuation over the full transect width at Tillingham, i.e. a. distance of 310m, averaged 92%. This figure translates into 0.3% wave height attenuation per meter cross-shore distance. Corresponding values were negative (i.e. indicating wave height increases) at –58% (over a distance of 112m) at Bridgewick, translating into a spatial average of -0.52% per meter cross-shore distance.

A simple division of each of the sites into 'mudflat' and 'saltmarsh' sections results in average wave height (H_s) attenuation values of:

Tillingham mudflat:	20.57% over 147m (i.e. 0.14%/m)
Tillingham saltmarsh:	87.37% over 163m (i.e. 0.54%/m)
Bridgewick mudflat:	-23.91% over 102m (i.e. –0.23%/m) (i.e wave increase)
Bridgewick saltmarsh:	43.81% over 10m (i.e. 4.38%/m)

In terms of wave energy (Joules/m2), average attenuation over the entire transect was 99% (i.e. 0.3% per meter) at Tillingham and –80% (i.e. -0.7% per meter) at Bridgewick. When these figures are split into the mudflat and saltmarsh sections of the transects, the following attenuation averages result:

Tillingham mudflat:	35.25% over 147m (i.e. 0.24%/m)
Tillingham saltmarsh:	98.92% over 163m (i.e. 0.61%/m)
Bridgewick mudflat:	-55.06% over 102m (i.e. –0.54%/m) (i.e wave increase)
Bridgewick saltmarsh:	79.13% over 10m (i.e. 7.91%/m)

The high spatial density of wave recorders deployed in this study, however, makes it possible to resolve the wave attenuation process across the marsh surface further. Figure 7 shows average significant wave energy height dissipation for the different sections between individual pressure sensors of the Tillingham and Bridgewick transects respectively. Average wave height attenuation is minimal across the 147m and 87m wide mudflat sections of the transect at Tillingham (sensors 14-10 in Figure 7(a)) and Bridgewick (sensors 17-18 in Figure 7(b)) respectively. Conversely, average wave energy attenuation is at a maximum immediately landward of the marsh edge (across the first 10 meters of permanent vegetation cover) at both sites (2.12%/m between sensors 8-9 at Tillingham and 1.14%/m between sensors 20-21 at Bridgewick).

Immediately seaward of the cliff face at Bridgewick, average wave height and energy experience an abrupt increase (i.e. negative attenuation; average of –0.26%/m).

At Tillingham (Figure 7(a)), while average wave height attenuation increases abruptly as waves travel across the first 10 meters of the permanently vegetated marsh (sensors 8-9), a gradual decrease in attenuation can be observed towards the back of the marsh, at a distance of 60-120m landward of the marsh edge (0.34%/m between sensors 1-4). At these landward locations, attenuation is comparable to the average attenuation recorded for the 23m section across the unvegetated mudmound topography of the mudflat (0.20%/m between sensors 13-10).

Relationship between water depths and wave attenuation

No significant correlation exists between measured water depths and wave attenuation with the exception of the transect sections immediately landward of the marsh edge (i.e. sensors 9-8 and 8-5 at Tillingham and sensors 20-21 at Bridgewick). The relationship between water depth at the most seaward sensor (on the mudflat) and wave attenuation along these three transect sections is statistically significant ($p = 0.05$) and can be expressed with the following regression equations (where x = water depth (m) and E_{red} = wave energy reduction):

i. Across the first 10m of permanent vegetation (between sensor 9 and 8):

E_{red} (%/m) = -7.9 x + 17.5 $r^2 = 0.69$

ii. Across the following 28m of permanent vegetation (between sensor 8 and 5):

E_{red} (%/m) = -3.3 x + 8.9 $r^2 = 0.75$

iii. Across the first 10m of permanent vegetation landward of a marsh edge cliff:

E_{red} (%/m) = -1.2 x + 3.5 $r^2 = 0.47$

If the water depths at the marsh edge (instead of the mudflat) are used as the independent variable, the relationships derived are as follows:

i. Across the first 10m of permanent vegetation (between sensor 9 and 8):

E_{red} (%/m) = -8.1 x + 8.7 $r^2 = 0.69$

ii. Across the following 28m of permanent vegetation (between sensor 8 and 5):

E_{red} (%/m) = -3.7 x + 5.3 $r^2 = 0.83$

iii. Across the first 10m of permanent vegetation landward of a marsh edge cliff:

E_{red} (%/m) = -11.6 x + 13.9 $r^2 = 0.64$

Seasonal variation in wave energy dissipation

Averages of significant wave heights and wave height attenuation for three periods of the year (autumn: September – November 2000, winter: December 2000 – February 2001, and spring: March – July 2001) are shown in Figure 8. At all sensors, the highest seasonal significant wave height averages were recorded in the period December to February (Figure 8(a)). Wave heights were significantly lower in the autumn and spring, although averages in spring (March – July) exceeded those autumn (September – November).

In terms of significant wave height attenuation (Figure 8(b) and (c)), little seasonal difference exists between attenuation on the mudflats and at the landward sections of the Tillingham site. Significant differences in wave attenuation, however, can be observed at the marsh edge at Tillingham (between sensors 10-9, 9-8, and 8-5) and in front of the cliff at Bridgewick (between sensors 19-20). At Tillingham, a consistent decrease in attenuation can be observed from autumn through winter and into spring. In front of the cliff at Bridgewick, a similar change can be observed with wave attenuation becoming negative (i.e. wave energy/height increase occurring) in the spring period.

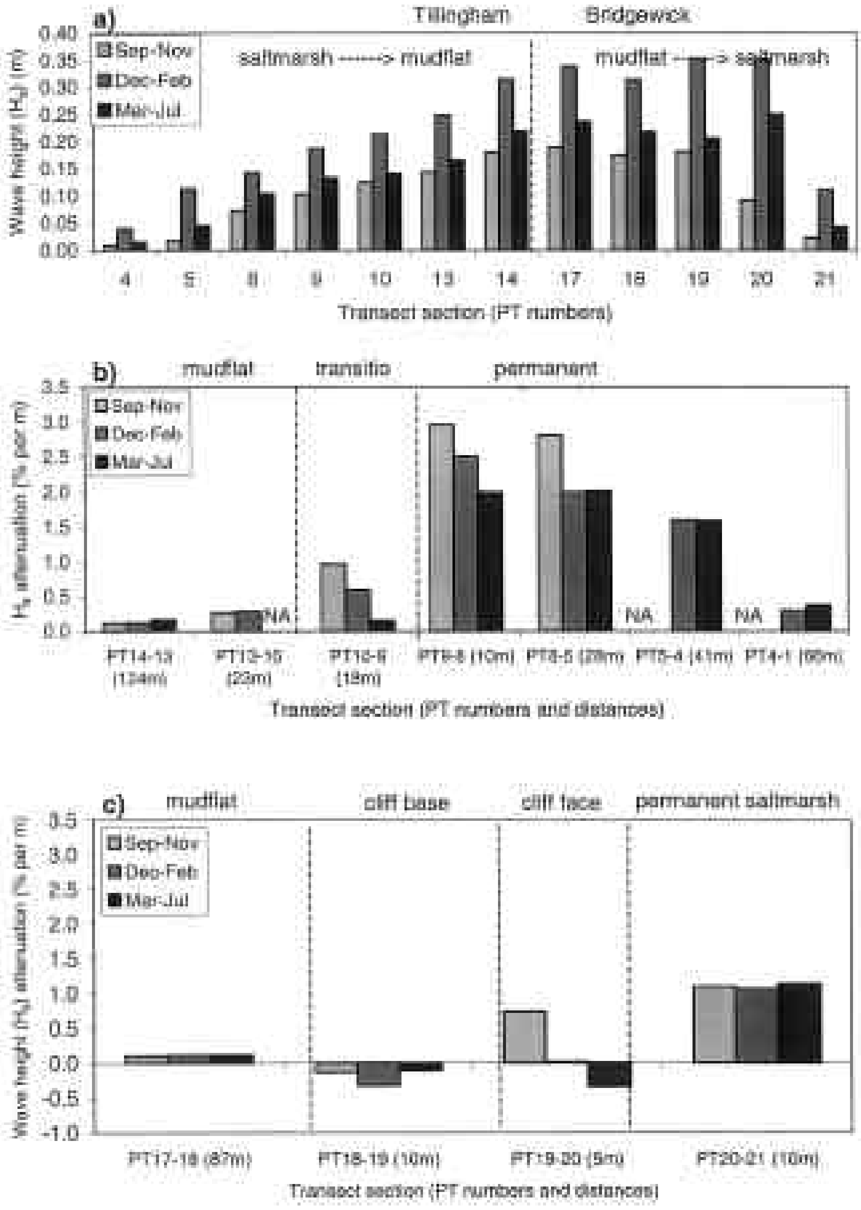

Figure 8. Mean significant wave heights (a) and mean significant wave height dissipation across individual transect sections at (b) Tillingham and (c) Bridgewick

Seasonal vegetation changes

Results from the vegetation survey of November 2000, February 2001, and June 2001 are summarised in Figure 9 (see Figures 4 and 5 for locations of vegetation monitoring stations T1-5 and B1-3), which illustrates the general, progressive increase in vegetation density away from the marsh edge towards the marsh interior. At Tillingham, vegetation density reaches a peak at site T3 in the centre of the marsh before decreasing landwards towards site T5.In general, densities were highest in November and lowest in February, although local variability between the vegetation monitoring locations was high. Between November and February, vegetation density (as projected into the vertical plane used for the photographs) decreased at all three sites at Bridgewick (by over 65%) but only at the seaward (T1) and landward (T5) marsh edge at Tillingham (by ca. 80%) (Figure 9). Between February and June, however, vegetation density increased by over 200% at the most landward monitoring locations at Bridgewick (B3) and Tillingham (B5). Further seaward, the decreasing trend in density that characterised the change from November to February continued (Figure 9).

In terms of species composition, the most prominent seasonal changes were associated with the disappearance of Salicornia spp. from the most seaward location at Tillingham (T1) and the appearance of algae at the same location. Interestingly, the most seaward location on the marsh cliff at Bridgewick (B1), also showed a significant decrease in Spartina spp. throughout the monitoring period from November 2000 to June 2001. All other locations remained relatively stable through time with respect to their species composition.

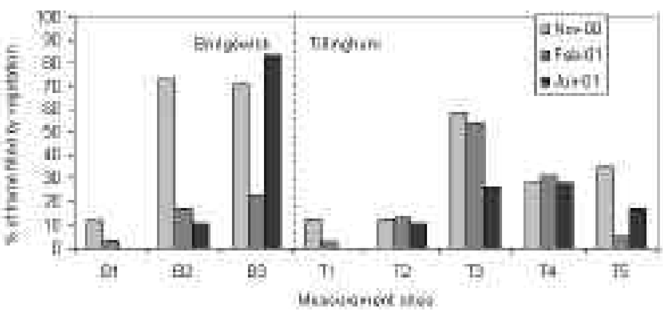

Figure 9. Seasonal changes in vegetation density (for location of sites on the cross-shore transect, see Figure 4 and 5)

DISCUSSION AND CONCLUSIONS

General patterns of wave transformation at Tillingham and Bridgewick

The results from the wave measurements carried out at Tillingham and Bridgewick provide the most comprehensive dataset yet available to assess the potential sea defence value of marshes characterised by different marsh edge morphologies and different incoming wave energies. The results from Tillingham can be directly compared with previous work at Stiffkey, N. Norfolk, U.K. (MÖLLER *et al*., (1999) due to the similar marsh-mudflat morphology and transect length.

It is useful to consider the differences in environmental setting and hydrodynamic context of the three sites before proceeding to a comparison between the sites. At Stiffkey (MÖLLER *et al*., (1999), water depths encountered during wave recording on the marsh surface immediately landward of the marsh edge, ranged from 0.5 to 1.4m. At Tillingham and Bridgewick, however, the marsh surface was considerably (ca. 45cm) higher in the tidal frame, resulting in lower water depths at the marsh edge (sensors 9 and 20), of 0.1 to 0.8 and 1.0m respectively. Seaward of the marsh edge, relative elevations of the Tillingham mudflat were similar to the Stiffkey sandflat, and water depths at the outermost recording stations at Tillingham (1.0 to 2.0m) are only slightly higher than at Stiffkey (0.9 to 1.8m). At Bridgewick, however, the low mudflat elevations relative to the other two sites, lead to a much wider range of water depths being encountered (0.5 to 2.7m).

Not withstanding differences in offshore topography and nearshore wave transformations, these differences in water depths alone would lead one to expect differences in incoming wave energy at the three sites. Given the increased water depths on the mudflats of the Dengie Peninsula, and the high exposure of these marshes to waves from the North Sea, it is not surprising to find that, at 715 Joules/m2, the maximum incoming total wave energy recorded at Bridgewick (highest water depths) is 1.5 times higher than at Tillingham (464 Joules/m^2), and 2.6 times higher than at Stiffkey (277 Joules/m^2). One might expect, therefore, differences in the overall wave attenuation over the two respective marshes. However, average wave energy dissipation over the Stiffkey saltmarsh and over the Tillingham marsh (see Figure 10), is strikingly similar. Both marshes attenuate wave energy at a rate of ca. 0.5%/m over the entire saltmarsh section. This similarity provides a strong indication that the effect of the lower water depths combined with higher incident wave energy on wave attenuation overall at Tillingham is minimal and/or offset by the influence of differences in topography or vegetation.

The Stiffkey study was not able to resolve changes in wave attenuation with distance across the marsh surface. The data from Tillingham, however, show that it is misleading to calculate average wave attenuation rates for the entire marsh section, as more than 40% of the wave energy that arrives at the marsh edge is attenuated across the first 10 metres of the permanently vegetated marsh. On average, the following 28 meters of marsh attenuate a further 60% of the wave energy. Given the overall similarity in the wave attenuation potential of the Tillingham and Stiffkey marshes, it is likely, that the Stiffkey marshes show a similar pattern of attenuation with distance from the marsh edge as is shown for Tillingham (Figure 7(a)).

Effect of marsh width and edge on wave attenuation

Most wave energy dissipation clearly occurs in the first few meters of the permanently vegetated saltmarsh. This general conclusion applies to the case of the non-cliffed as well as the cliffed site, although marsh edge wave energy dissipation is twice as high at the cliffed site at Bridgewick (average energy dissipation of ca. 8%/m) than at the smoother mudflat-to-saltmarsh transition at Tillingham (average of just over 4%/m).

Wave energy appears to increase immediately in front of (i.e. seaward) of the marsh cliff at Bridgewick (average of 8%/m increase over the five meters between sensors 19 and 20). This apparent high attenuation may be explained by a more complex process in which the interaction between wave energy reflection by the cliff face, wave shoaling (i.e. an increase in wave height due to a sudden decrease in water depths), and dissipation due to surface roughness all play important roles. Although the interaction of the cliff face with the incoming waves and the associated energy attenuation has a protective effect on the marsh surface landward of the cliff, this mechanism itself causes quasi-continuous cliff erosion. Given the high incoming wave energy at Bridgewick, the cliffed marsh edge is not a sustainable morphological configuration. In such conditions, a continued reduction in overall marsh width seems inevitable.

The ramped marsh edge at Tillingham appears to have a less complex effect on incoming waves as wave heights and energy gradually decrease across the mudflat and no increase occurs seaward of the seasonal to permanent vegetation transition zone. After the initially high reduction in wave energy (greater than 4%/m over the first 10 meters of vegetated marsh), wave attenuation rates decrease rapidly and are reduced to 0.5%/m after only ca. 80m. This rapid decrease in wave heights appears to be consistent with the findings of MÖLLER *et al*., (1999), who demonstrated that the results of the Stiffkey study could only be reconciled with BRAMPTON's (1992) physical scale model if all of the observed wave attenuation took place in the first 80m of saltmarsh.

Effect of water depth on wave attenuation

It has been suggested in a previous study (MÖLLER *et al*., (1999)) that the effect of water depth on wave attenuation is most apparent over saltmarsh (compared to the unvegetated mud/sandflat) and in shallow water depths (less than approximately 1m). The dataset collected in this study is characterised by overall lower water depths than those encountered previously at Stiffkey. Water depths at the marsh edge at Stiffkey (MÖLLER *et al*., (1999)) ranged from 0.52 and 1.39m, whereas depths at the marsh edge at Tillingham and at Bridgewick ranged from 0.12 to 0.84m and 0.12 to 1.04m respectively. One would thus expect water depth to exert a significant control on wave attenuation at Tillingham and Bridgewick.

Interestingly, the results show, that at the Dengie sites water depth has little control on wave attenuation, except for those sections of the transects that contain the most seaward edge of the saltmarsh (i.e. the sections between sensors 9 and 5 at Tillingham and between sensors 20 and 21 at Bridgewick). These transect sections correspond to those sections of the transects over which significant wave height dissipation is generally highest (Figure 7). This observation supports the findings from the earlier studies at Stiffkey, that suggested that the effect of water depth on wave attenuation is least significant in areas where attenuation is generally reduced (i.e. the Stiffkey sandflat or, in this case, the mudflats). The Stiffkey study, however, was not able to resolve the spatial differences in wave attenuation across the saltmarsh surface itself. The analysis of the data from Tillingham and Bridgewick with respect to the link between water depth and wave attenuation confirms that the first 10 meters landward of the marsh edge (as defined by the seaward edge of permanent vegetation cover) is the area where the vegetated surface has the strongest influence on incoming waves. The data from this study clearly confirms that water depths in this area are of critical significance to the wave attenuation process.

Effect of seasonal vegetation changes on wave attenuation

The results of the vegetation surveys (Figure 9) and the seasonal analysis of wave conditions and wave attenuation (Figure 8) provide some clues as to the potential importance of vegetational changes for the wave attenuation process.

As most of the observed wave attenuation occurs immediately landward of the permanently vegetated marsh edge, vegetational change in this region is likely to have an effect on the wave attenuation capacity of the marshes. At site T3 at Tillingham (Figure 4) seasonal vegetation density decreases from autumn (September – November) to spring (March – July) (Figure 9). Seasonal wave attenuation changes (sensors 9-8, Figure 8(b)) reflect these vegetation

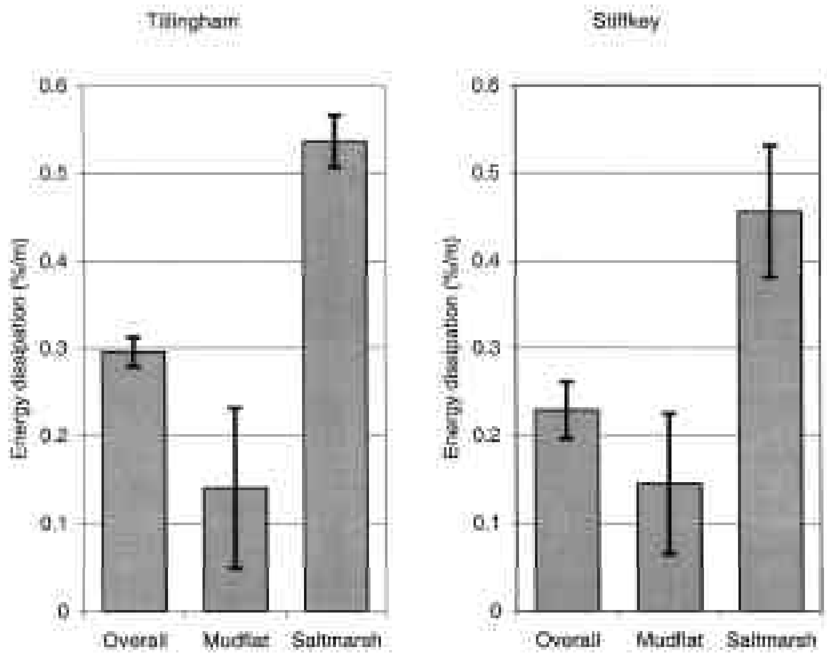

Figure 10. Mean wave energy dissipation over Stiffkey transect sections (Möller *et al*., 1999) compared to Tillingham transect sections (error bars represent +/- one standard deviation)

density changes. By comparison, in the marsh interior (site T4 (Figure 9) and transect section between sensors 5-4 (Figure 8(b)) negligible seasonal vegetation density changes correspond to minimal seasonal wave attenuation changes. At the landward limits of the marsh, however, this simple correspondence in the patterns of seasonal vegetation density change and wave attenuation change breaks down, although a small increase in vegetation density from the winter to the spring period is accompanied by an increase in wave attenuation (site T5, Figure 9; between sensors 4-1, Figure 8(b)). It is likely that the different response of wave attenuation processes to vegetational changes at the most landward areas of the marsh is due to the different vegetation community present. While the marsh vegetation at the marsh edge and in the interior marsh includes a significant percentage of *Salicornia* and *Suaeda* spp., landward sections of the marsh are dominated by *Puccinellia* spp., a flexible grass whose structural characteristics may impact less on wave dynamics.

At Bridgewick, wave attenuation across the marsh at the top of the cliff (Figure 8(c) between sensors 20-21) was not affected by the relatively marked seasonal change in vegetation density recorded (Figure 9 (vegetation measurement sites B1-B3)). A continuous decrease in vegetation density was observed at B1 and B2 throughout the monitoring period, but a high increase at B3 was observed at the end of the period (from winter to spring). The dominant species in this area were Spartina spp., characterised by a relatively rigid upright structure, which could be expected to contribute substantially to an increase in the hydraulic roughness of the surface. The fact that changes in vegetation density in this area had apparently little effect on wave attenuation may be explained by a dominating influence of the cliff over the influence of the marsh surface.

Acknowledgements

This study was carried out with financial support from the Environment Agency. CERU, UCL, under the direction of JR French, assisted with data collection. Calibration work formed part of a programme of research with P Ciavola (Universita di Ferrara) funded through the Royal Society Anglo-Italian Exchange Programme. We are grateful to A Hayes for assistance with the monitoring network design and construction and to A Whisker, F Thomalla, and M Theobald for assistance with installation and monitoring tasks. M Herman and H Schans kindly assisted with unpublished offshore wave and shore profile datasets respectively.

LITERATURE CITED

ADAM, P., 1978. Geographical variation in British saltmarsh vegetation. *Journal of Ecology*, 66, 339-366.

ALLEN, J.R.L., 1989. Evolution of salt-marsh cliffs in muddy and sandy systems: a qualitative comparison of British west-coast estuaries. *Earth Surface Processes and Landforms*, 14, 85-92.

ALLEN, J.R.L., 1990. Salt-marsh growth and stratification: a numerical model with special reference to the Severn estuary, southwest Britain. *Marine Geology* 95, 77-96.

ALLEN, J.R.L., and Rae, J.E. 1988. Vertical salt-marsh accretion since the Roman period in the Severn Estuary, Southwest Britain. *Marine Geology* 83, 225-235.

BRAMPTON, A.H., 1992. Engineering significance of British saltmarshes, pp. 115-122. *In*: ALLEN, J.R.L., and PYE, K., (Eds.), *Saltmarshes: morphodynamics, conservation and engineering significance*, Cambridge: Cambridge University Press.

CARPENTER, K.E., and Pye, K., 1996. *Saltmarsh change in England and Wales - Its history and causes.* 158pp. R and D Technical Report W12, HRWallingford Ltd.

COSTANZA, R.; D'ARGE, R., de GROOT, R., FARBER, S., GRASSO,m., HANNON, B., LIMBURG, K., NAEEM, S., O'Neill, R.V., PARUELO, J., RASKIN, R.G., SUTTON, P., and van den BELT ,m., 1997. The value of the world's ecosystem services and natural capital. *Nature*, 387, 253-260.

DALRYMPLE, R. A.; KIRBY, J. T. and HWANG, P. A., 1984. Wave diffraction due to areas of energy dissipation. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 10, (1), 67-79.

DAY, J.W.Jr.; BRITSCH, L.D., HAWES, S.R., SHAFFER, G.P., REED, D.J., and CAHOON, D., 2000. Pattern and process of land loss in the Missippi Delta: A spatial and temporal analysis of wetland change. *Estuaries*, 23, 425-438.

DIXON, A.M.; LEGGETT, D.J., and WEIGHT, R.C., 1998. Habitat creation opportunities for landward coastal re-alignment: Essex case studies. *Journal of the Institution of Water and Environmental Management*, 12, 107-112.

EDINGER, E., and BROWNE, D.R., 2000. Continental seas of Western Indonesia, pp. 381-404. *In*: SHEPPARD, C., (Ed.), *Seas at the Millenium: An environmental evaluation*. Amsterdam: Elsevier Science.

FLATHER, R., 1987. Estimates of extreme conditions of tide and surge using a numerical model of the North-west European continental shelf. *Estuarine, Coastal and Shelf Science*, 24, 69-93.

FRENCH, J.R., 1993. Numerical modelling of vertical marsh growth and response to rising sea-level, Norfolk, U.K. *Earth Surface Processes and Landforms*, 18, 63-81.

FRENCH, J.R., and REED, D.J., 2001. Physical contexts for saltmarsh conservation, pp. 179-228. *In*: WARREN, A., and FRENCH, J.R., (Eds.), *Habitat conservation: Managing the physical environment*. Chichester: John Wiley.

GRAMOLT, D.W., 1960. *The coastal marshlands of East Essex between the 17th and mid-19th centuries*. Unpublished M.A. dissertation, University of London.

GREENSMITH, J.T., and Tucker, E.V., 1965. Saltmarsh erosion in Essex. *Nature*, 206,

GREENSMITH, J.T., and Tucker, E.V., 1973. Holocene transgressions and regressions on the Essex coast, Outer Thames Estuary. *Geologie en Mijnbouw*, 52, 193-202.

GREENSMITH, J.T., and TUCKER, E.V., 1975. Dynamic structures in the Holocene chenier plain setting of Essex, England. pp. *In*: HAILS, J., and CARR, A., (Eds.), *Nearshore sediment dynamics and sedimentation*, Chichester: John Wiley.

HARMSWORTH, G.L., and Long, S.P., 1986. An assessment of saltmarsh erosion in Essex, England, with reference to the Dengie Peninsula. *Biological Conservation*, 35, 377-387.

HERMAN, W.M., 1999. *Wave dynamics in a macro-tidal estuary*. Unpublished Ph. D. dissertation, University of Cambridge.

HOWELL, G.L., 1998 Shallow water directional wave gages using short baseline pressure arrays. *Coastal Engineering*, 35, 85-102.

HUTHNANCE, J.M., 1991. Physical oceanography of the North Sea. *Ocean and Shoreline Management*, 16, 199-231.

JACOBSEN, N.K., 1980. Form elements of the Wadden Sea area, pp.50-71. *In*: DIJKEMA, K.S., (Eds). *Geomorphology of the Wadden Sea area*. Rotterdam: Balkema.

JUNGERIUS, P.D., and Van der Meulen, F., 1988. Erosion processes in a dune landscape along the Dutch coast. Catena, 15, 217-228.

KNUTSON, P.L; Seeling, W.N., and Inskeep,M.R., 1982. Wave damping in Spartina alterniflora marshes. *Wetlands*, 2, 87-104.

KOBAYASHI, N.; RAICHLE, A. W. and ASANO, T., 1993. Wave attenuation by vegetation. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 119, (1), 30-48.

LEONARD, L.A.; HINE, A.C., and LUTHER,M.E., 1995. Surficial sediment transport anddeposition processes in a Juncus roemerianus marsh, west-central Florida. *Journal of Coastal Research*, 11, 322-326.

MITSCH, W.J., and GOSSELINK, J.G., 1993. *Wetlands*. New York: Van Nostrand Reinhold.

MOELLER, I.; SPENCER, T., and FRENCH, J.R., 1996. Wind wave attenuation over saltmarsh surfaces: preliminary results from Norfolk, England. *Journal of Coastal Research*, 12, 1009-1016.

MÖLLER, I.; SPENCER,T., FRENCH, J.R., DIXON,M., and Leggett, D.J., 1999. Wave transformation over salt marshes: a field and modelling study from North Norfolk, England. *Estuarine, Coastal and Shelf Science*, 49, 411-426.

NICHOLLS, R.J.; HOOZEMANS, F.M.J., and MARCHAND,M., 1999. Increasing flood risk and wetland loss due to global sea-level rise: regional and global analyses. *Global Environmental Change - Human and Policy Dimensions*, 9, 69-87.

PETHICK, J.S., 1992. Saltmarsh geomorphology. pp. 41-62. *In*: ALLEN, J.R.L., and PYE, K., (Eds.), *Saltmarshes: morphodynamics, conservation and engineering significance*, Cambridge: Cambridge University Press.

PETHICK, J.S., and REED, D.J., 1987. Coastal protection in an area of slat marsh erosion, pp1094-1104. *In*: KRAUS, N.C., (Ed.), *Coastal Sediments* ‘87, ASCE

PRINGLE, A.W., 1995. Erosion of a cyclic salt-marsh in Morecambe Bay, northwest England. *Earth Surface Processes and Landforms*, 20, 387-405.

PYE, K. and FRENCH, P.W., 1993. *Erosion and accretion on British saltmarshes. Volume 3*: National survey of accretion and erosion status. MAFF

REED, D.J., 1988. Sediment dynamics and deposition on a retreating coastal saltmarsh. *Estuarine, Coastal and Shelf Science*, 26, 67-79.

SHI, Z.; HAMILTON, L.J., and WOLANSKI, E., 2000. Near-bed currents and suspended sediment transport in saltmarsh canopies. *Journal of Coastal Research*, 16, 909-914.

SHI, Z.; PETHICK, J.S., and PYE, K., 1995. Flow structure in and above the various heights of a saltmarsh canopy: a laboratory flume study. *Journal of Coastal Research*, 11, 1204-1209.

SMITH, G.M.; SPENCER, T., MURRAY, A.L. and FRENCH, J.R., 1998. Assessing seasonal vegetation change in coastal wetlands with airborne remote sensing: an outline methodology. *Mangroves and Salt Marshes*, 2, 15-28.

STEERS, J.A.; STODDART, D.R., BAYLISS-SMITH, T.P., SPENCER, T. and DURBIDGE, P.M., 1979. The storm surge of 11 January 1978 on the east coast of England. *Geographical Journal*, 145, 192-205.

STUMPF, R.P., 1983. The process of sedimentation onthe surface of a saltmarsh. *Estuarine, Coastal and Shelf Science*, 17, 495-508.

TITUS, J.G., 1991. Greenhouse effect and coastall wetland policy: How Americans could abandon an area the size of Massachusetts at min imum cost. *Environmental Management*, 15, 39-58.

TWILLEY R.R.; Chen R.H. and Hargis T., 1992. Carbon sinks in mangroves and their implications to carbon budget of tropical coastal ecosystems. *Water, Air and Soil Pollution*, 64, 265-288.

VAN EERDT, M., 1985. Salt marsh cliff stability in the Oosterschelde. *Earth Surface Processes and Landforms*, 10, 95-106.

WANG, F.C.; Lu, T.S., and SIKORA, W.B., 1993. Intertidal marsh suspended sediment transport processes, Terrebonne Bay, Louisiana. *Journal of Coastal Research*, 9, 209-220.