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Tidal marsh sedimentation and resilience to environmental change: Exploratory modelling of tidal, sea-level and sediment supply forcing in predominantly allochthonous systems

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Abstract

The existence and function of tidally dominated and predominantly allochthonous marshes are ultimately contingent upon the operation of hydrodynamic and sedimentary processes within constraints imposed by the available accommodation space and sediment supply. This paper re-interprets published data relating to contemporary vertical marsh growth and sea-level rise in the context of the conceptual model relating elevation, sedimentation, sea-level rise, sediment supply and tidal range. This analysis is supported by numerical mass balance modelling of the equivalent parameter space and of the sensitivity of marsh hydroperiod and sedimentation to sea-level and sediment supply forcing. The effect of autocompaction on the translation of sedimentation into elevation change is also considered.

Parameter space modelling provides a framework for the interpretation of field data and affords indicative insights into marsh resilience to change. It is argued that the assessment of marsh response to external environmental forcing should be based not on empirical comparisons of sedimentation versus sea-level rise but on the estimation of sediment supply, and the efficiency with which this is depleted by deposition, as metrics of marsh resilience. This implies a shift towards more intensive process studies aimed at elucidating more fully the linkages between tidal marshes and adjacent estuarine and coastal systems.

Model results also indicate significant variability in marsh sedimentation associated with 18.6 yr tidal modulation and meteorological processes at short-term scales. Such variability further complicates the interpretation of sedimentation or elevation change data obtained from monitoring programmes of short duration. Longer-term monitoring is of value, however, as a means of identifying important mechanisms of climate and sediment supply forcing that may contribute to the formation and maintenance of marsh sedimentary sequences.

Keywords: tidal saltmarsh; sedimentation; sediment budget; sea-level rise; autocompaction; numerical modelling; North Atlantic Oscillation

1. Introduction

Saltmarshes are widely distributed within the high intertidal zone of mid to high latitudes and have been extensively studied with regard to their contribution to coastal and estuarine stratigraphic sequences (Redfield, 1972; Frey and Basan, 1985; Allen and Rae, 1987) and the sedimentary processes governing their morphodynamic behaviour over a range of timescales (Allen, 2000; French and Reed, 2001; Friedrichs and Perry,

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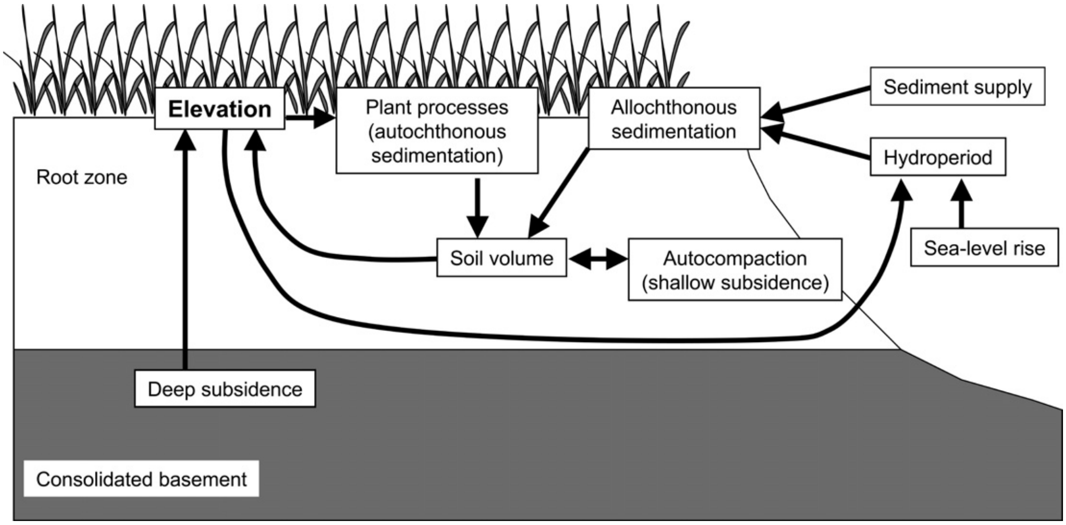

Fig. 1. Conceptual model of the principal factors governing adjustment of marsh elevation within the tidal frame. Modified from USGS (1997).

2001). Saltmarshes are also increasingly appreciated as ecologically valuable wetland habitats and as a key component of coastal and estuarine food chains (e.g. Nixon, 1980; Gordon et al., 1985; Zedler and Callaway, 2001). A more-or-less continuous cover of salt-tolerant macrophytes is an integral part of the saltmarsh definition (French, 2003) and these systems are often portrayed as highly productive wetlands in which physical processes are largely subservient to biological factors. However, the existence and ecological function of tidally-dominated saltmarshes are ultimately contingent upon the operation of hydrodynamic and sedimentary processes within constraints imposed by the intertidal accommodation space and the sediment supply. An understanding of morphostratigraphy (Allen, 2000) thus provides an essential framework for the understanding of marsh functioning as sediment sinks, and their geomorphological and ecological response to external environmental forcing.

Conceptual models of saltmarsh morphodynamic behaviour must take account of a diverse spectrum of marsh types that reflects broad continua of environmental controls as well as qualitative contrasts in processes. Whilst a global model is probably neither feasible nor desirable, much of the observed diversity can be accommodated by envisaging variations upon the schematisation shown in Fig. 1. This identifies the elevation of the marsh sedimentary platform as a crucial system state variable that represents the net outcome of allochthonous and autochthonous contributions to substrate volume. Following Dijkema (1987), it is logical to make a qualitative distinction between predominantly allochthonous marshes formed chiefly through the accumulation of externally-derived clastic sediments and autochthonous marshes in which plant productivity is the critical factor determining the maintenance of elevation relative to the tidal frame. Autochthonous marshes typically occur in micro-tidal settings, with the relative contribution of allochthonous sediments increasing with tidal range. These broad generalisations provide a basis for the identification of systems exhibiting broadly similar morphodynamic behaviour and for the conduct of regional case studies in a manner that contributes to wider principles. The value of such an approach is well exemplified by Allen's (2000) meticulous review sketch of the saltmarshes of northwest Europe.

Within the highly allochthonous saltmarshes fringing the southern North Sea coasts of northwest Europe, the linkage between surface elevation, tidal inundation, and sedimentation is especially strong and constitutes a form-process feedback that conditions vertical marsh growth timescales on the order of 10^1 to 10^3 yr. The asymptotic nature of marsh elevation — time trajectories was first investigated empirically in Pethick's (1981) classic study of backbarrier marshes in north Norfolk, UK. Sedimentary infilling of the tidal frame, and factors controlling the attainment of an equilibrium marsh elevation have also been modelled numerically (Krone, 1987; Allen, 1990, 1991; French, 1993, 1994). As Allen (2000) notes, all these models are aspatial (i.e. zero-dimensional) and involve some form of time-stepping numerical simulation of the basic mass balance equation

$$\Delta E = \Delta S_{\mathrm{min}} - \Delta S_{\mathrm{org}} - \Delta M - \Delta P \quad (1)$$

where ΔE is the change in marsh surface elevation relative to a (potentially moving) tidal frame of reference, ΔS_{min} is the added thickness of externally-derived clastic sediment, ΔS_{org} is the additional thickness of intrinsically-derived organic sediment, ΔM is the change in relative sea-level (upward positive) and ΔP is the elevation change due to autocompaction of the marsh deposit above an incompressible basement. Numerical articulation of this basic scheme at an annual time step over 10^2 to 10^3 yr timescales reveals the vertical marsh growth trajectories that are characteristic of contrasting sea-level and sediment supply scenarios (Allen, 1991; French, 1993; Temmerman et al., 2003). More recent work has included more complete representation of organic accumulation (Callaway et al., 1996) and the hitherto rather neglected autocompaction term (Allen, 1999). In North America, similar mass balance schemes have been coupled to ecosystem models to permit more realistic simulation of predominantly autochthonous systems (e.g. Simas et al., 2001; Morris et al., 2002).

Attention has focused on the perceived vulnerability of saltmarshes to accelerated rates of sea-level rise (Orson et al., 1985; Reed, 1990; Simas et al., 2001). Several modelling studies have addressed this, notably the extrapolations of historic marsh growth by French (1993, 1994) and Temmerman et al. (2003). With respect to autochthonous marshes, Morris et al. (2002) have also modelled the impact of sea-level variation and trend on plant productivity and marsh elevation. But much use continues to be made of empirical comparisons between measured rates of sediment accumulation and local sea-level trends as a basis for inferences concerning the ability of marsh elevations to track rises in mean sea-level (Orson et al., 1998) and the extent to which historic marsh sedimentation provides a surrogate measure of sea-level rise (e.g. Cundy and Croudace, 1996). The concept of net vertical sedimentary balance – that is the difference between rates of sedimentation and sea-level rise – is important here (Stevenson et al., 1986; French, 1994) and most studies of saltmarsh sedimentation now include a comparison of this kind. However, the statistical basis for comparisons of sedimentation and sea-level rise is often dubious (French, 1994). More importantly, interpretation of a sedimentation deficit or surplus as a measure of vulnerability to sea-level rise ignores the complexity of marsh response that arises from the linkages represented in Eq. (1).

This overview paper re-interprets published data relating to contemporary vertical marsh growth and sea-level rise in the context of the conceptual model of marsh morphodynamics outlined above. This analysis is supported by exploratory modelling of the parameter space defined by marsh elevation, sedimentation, sea-level rise, sediment supply and tidal range. A simple zero-dimensional mass balance scheme is used to model the empirical data envelope, thereby providing a framework for more intensive analysis of individual case study systems. It is argued that studies of marsh response to accelerated sea-level rise should focus not on crude measures of net sedimentary balance but on the estimation of sediment supply, and the efficiency with which this is depleted by deposition, as metrics of marsh resilience to external forcing.

2. Research approach

There are two main elements to the study. The first comprises an analysis of published data relating to rates of tidal marsh sedimentation in order to establish the envelope of variability with respect to sea-level rise, tidal range and (insofar as is possible) sediment supply. The second involves exploratory numerical modelling to establish the natural bounds of the equivalent parameter space and to investigate the sensitivity of individual systems to variability and trend in the main external forcing factors.

2.1. Inventory of marsh sedimentation data

The synthesis of published data updates earlier work by French (1994), which was, in turn, inspired by analyses of US East and Gulf coast data by Stevenson et al. (1986) and Wood et al. (1989). The new inventory incorporates data from studies of predominantly allochthonous tidal marshes in Europe and North America. The main criteria for inclusion were:

– availability of either spatially-averaged or spatially-distributed data on marsh sedimentation and/or actual elevation change at annual to decadal timescales;
– availability of information on tidal range and sea-level trend;
– where possible, the existence of data relating to indicative suspended sediment concentrations within the marsh system in question or in adjacent coastal or estuarine waters.

Empirical generalisations based on geographically extensive sampling of this kind are necessarily limited in their explanatory power, largely due to the inherent difficulty in reconciling data acquired using a variety of techniques and in inferring general principles of system behaviour from a diverse sample of individual cases influenced to a varying extent by locally-specific factors. These difficulties were mitigated as far as possible by careful screening to exclude studies reporting only limited or short duration data (specifically, studies with <2 yr of data were excluded). This reduces the sample size, but is necessary to avoid obviously spurious estimates of decadal-scale behaviour, especially in systems driven by highly intermittent sedimentation events. Marshes known to be influenced by factors not represented in the conceptual model of Fig. 1 (notably ice action) were also excluded. A crucial assumption made here is that measured rates of sedimentation are equivalent to actual changes in elevation. Cahoon et al. (1995) draw attention to the danger of this assumption in marshes characterised by significant autocompaction (or 'shallow subsidence') within the marsh sediment profile. However, field investigations in the UK by Cahoon et al. (2000) and French and Burningham (2003) show that sedimentation and elevation change are often statistically indistinguishable within well-established and highly allochthonous saltmarshes. The two measures are considered to be equivalent here, an assumption that, whilst inappropriate for detailed site-specific analyses, does not materially affect the conceptual arguments that follow.

Corresponding data relating to sea-level rise were derived either from the original studies or from independent analysis of the nearest reliable tide gauge records. Linear trends in relative sea-level rise are typically derived from data spanning several decades, which almost invariably exceed the duration of saltmarsh sedimentation or elevation change monitoring. This is reasonable given the lack of clear non-linearity in most tide gauge records over the last 20 to 40 yr (e.g. Woodworth, 1990; Douglas, 1992), although the representation of sea-level forcing as a linear trend clearly obscures important variability in forcing that one might expect to contribute to variability in sedimentation: this is considered further within the numerical modelling component outlined below.

Estimation of potential sediment supply is more problematic. There are still relatively few quantitative studies of suspended sediment exchange between saltmarshes and coastal or estuarine waters. Fewer still have focused directly on fine sediment dynamics within the overmarsh water column and the efficiency with which vegetated marsh surfaces trap tidally advected material (the work of van Proosdij et al. (2006) being a recent exception). Derivation of indicative time-averaged background suspended sediment concentrations is, in any case, a rather arbitrary exercise given the large spatial gradients in concentration and time variation over multiple scales. Reliable suspended sediment data are thus extremely sparse.

2.2. MARSH-0D numerical mass balance model

MARSH-0D is an evolution of the mass balance model used by French (1993, 1994). The underlying numerical scheme is similar to that of Krone (1987) and Allen (1990, 1991), but incorporates elements of later models by Callaway et al. (1996) and Temmerman et al. (2003). Applied to predominantly allochthonous systems, the dominant term driving the elevational adjustment of the marsh surface is the settling from suspension of fine-grained sediment advected into the marsh by tidal inundation. Elevation determines the number and duration of flooding events, during each of which sediment deposition is modelled as the product of a characteristic settling velocity and a depth-averaged (but time-varying) suspended sediment concentration. Sedimentation is cumulated over 1 yr time step and translated into net elevation change (relative to the tidal frame) by taking account of the bulk density at the time of deposition and (optionally) the effect of post-depositional autocompaction.

Following Krone (1987), the progressive exhaustion of the overmarsh suspended sediment reservoir is modelled using a mass balance scheme of the form

$$
\begin{aligned}
[h-E]\mathrm{d}C/\mathrm{d}t &= -w_{\mathrm{s}}C(t) + C_{\mathrm{flood}}\mathrm{d}h/\mathrm{d}t \\
[h-E]\mathrm{d}C/\mathrm{d}t &= -w_{\mathrm{s}}C(t) + C(t)\mathrm{d}h/\mathrm{d}t
\end{aligned}
\qquad (2)
$$

where h is the tidal water elevation, E is the elevation of the marsh surface, C_{flood} is the background suspended sediment concentration within water entering the marsh, $C(t)$ is the time-varying concentration within the overmarsh water column, and w_{s} is the particle settling velocity. This representation envisages particle settling occurring progressively throughout each tidal inundation event and not solely during brief 'slack water' periods. The assumption is also made that particles settling to the marsh surface are not re-suspended either on the ebb tide or during successive tides. Both these assumptions are supported by field evidence from northwest European marshes (e.g. Reed et al., 1999; Temmerman et al., 2003), which show that much of the incoming sediment is lost from suspension prior to high water and that re-suspension on the following ebb tide is minimal. Also, both empirical and theoretical studies show that incident wave energy is attenuated extremely rapidly within vegetated marsh canopies (Moller et al., 2001). Thus, in contrast to tidal flats, it is reasonable to neglect wave effects on particle settling and re-suspension (though not necessarily in extreme macro-tidal settings where maximum inundation depths are very large; see van Proosdij et al., 2006).

Krone (1987) modelled settling velocity empirically as a function of concentration. However, there is little evidence for systematic variation in w_s at the low concentrations (order 100 mg l^{-1}) that are typical of saltmarsh environments (see, for example, Teeter, 2001) and it is more convenient to represent w_s as a constant. Following French (1993), w_s is here assigned a default value of 1×10^{-4} m s^{-1}. This approach and value for w_s are also consistent with field observations of w_s by (Temmerman et al., 2003). The parameterisation of C_{flood} can also be handled with varying degrees of sophistication. French (1993) used a constant value, based upon available field data, to represent long-term average sediment supply: tidal, seasonal and interannual variability in concentration were thus subsumed within the model calibration process. Temmerman et al. (2003) model C_{flood} as a seasonally weighted empirical function of the tidal amplitude. This significantly improves the ability to model the early stages of rapid marsh growth but has less influence on the asymptotic decline in sedimentation rate as a dynamic equilibrium elevation is approached. It requires additional data and, more important, any functional relationship between sediment concentration and tidal amplitude is likely to be location specific. For the exploratory modelling undertaken here, therefore, MARSH-0D represents C_{flood} as a constant. Although deposition depletes the over-marsh suspended sediment reservoir during individual tidal inundation events, it is assumed that the sequestration of sediment by marsh deposition does not diminish the wider coastal or estuarine supply.

MARSH-0D directly simulates each successive tidal inundation event in a given year. Tidal levels are obtained either from an appropriate gauge record (in which case hourly or 15 min levels are interpolated to a 5 min simulation interval) or modelled using a minimal set of harmonic constituents. Secular variation in both mean sea-level and tidal amplitude can be applied either as time-dependent functions or from annual time-series data.

Both French (1993) and Allen (1991) used a small constant term to represent a modest autochthonous contribution to the marsh sedimentary fabric. MARSH-0D does incorporate a more sophisticated representation of organic accumulation, along the lines of Callaway et al. (1996). For the present purposes, however, this is not used, and the autochthonous term (S_{org} in Eq. (1)) is set to zero.

Although recent marsh modelling studies have included some representation of sediment autocompaction (e.g. Callaway et al., 1996; Temmerman et al., 2003) this term has generally been assumed to be small in sequences formed chiefly of silts and clays (e.g. French, 1993) and in stratigraphically thin marshes overlying backbarrier gravel or sand bodies (e.g. Bartholdy et al., 2004). However, Allen (1999) has demonstrated the potential importance of autocompaction in deeper sedimentary sequences, even those dominated by silt and clay. Drawing upon the work of Skempton (1970), he modelled the basic effect of autocompaction as an asymptotic function of the form

$$T = (T_0 - T_{min})e^{-kH} + T_{min} \tag{3}$$

where T is the final thickness of a compacted sediment layer, T_0 is the thickness at the time of deposition, T_{min} is the limiting thickness for zero porosity, H is the time-dependent thickness of the sediment overburden and k is a compressibility coefficient that can be determined empirically from vertical bulk density profiles. This idealised scheme is implemented in MARSH-0D, and can be used to examine the effect of autocompaction as a factor modifying rates of deposition through progressive post-depositional thinning of depositional increments.

2.3. Exploratory modelling

Two sets of MARSH-0D simulations are presented. The first, involves evaluation of the model for a marsh at a given elevation within the tidal frame across a parameter space defined by mean spring tidal range (range 0.5 to 5.5 m) and sediment supply (time-averaged background sediment concentration 25 to 250 mg l^{-1}). In these simulations, net change in accommodation space (i.e. the difference between sedimentation-induced elevation change and the rate of sea-level rise) is used as a system state parameter. Simulations are performed for marshes at two relative elevations: MHWN — corresponding to low, pioneer marsh; and MHWS — corresponding to a high established marsh. Various sea-level rise scenarios are modelled, including stability (M=0 mm a^{-1}); typical historic (M=2 mm a^{-1}); and accelerated (M=5, 10 and 15 mm a^{-1}). The results are evaluated against published data. The second set of simulations investigates in more detail the sensitivity of hypothetical marsh systems to variability and trend in sea-level and to changes in sediment supply. The role of autocompaction as a factor influencing the translation of short-term sedimentation into elevation change is also considered.

3. Results and analysis

3.1. Marsh sedimentation versus sea-level rise

Rates of sedimentation (or, in a few cases, actual elevation change) within a broad sample of predominantly allochthonous European and North American tidal marshes range from a few mm a^{-1} to several cm a^{-1} (Fig. 2A). Whilst there is no obvious trend in mean sedimentation rate with tidal range, the envelope of variability is wider at larger tidal ranges. There is no evidence for widespread vertical sedimentation or elevation deficits (Fig. 2B), although a few individual locations within some marshes (indicated by the lower end of their indicated ranges) have sedimentation rates lower than local sea-level rise. A single system shows a deficit (of about 1.6 mm a^{-1}) on this plot. This is

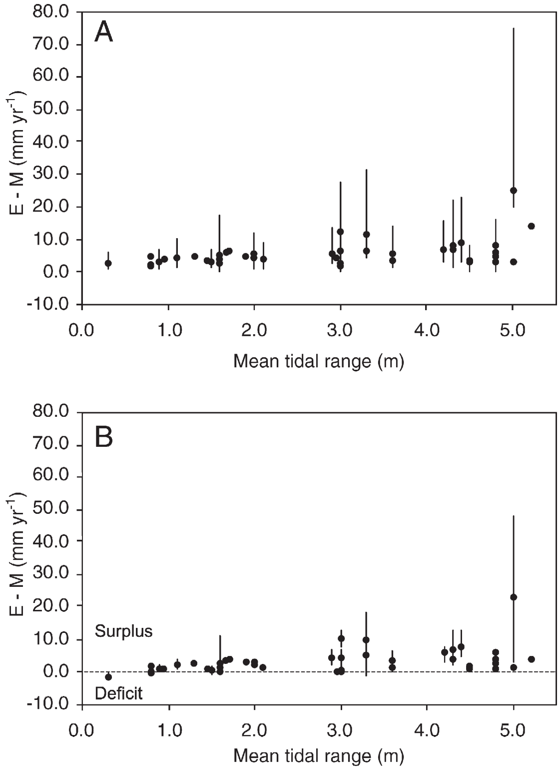

Fig. 2. A) Plot of elevation change, E, against mean tidal range for sample of northwest European and North American allochthonous marshes. Vertical bars represent range in reported sedimentation or elevation change rates within individual marsh systems. Data for northwest European marshes compiled from: Danish Wadden Sea (Skallingen): Bartholdy et al. (2004), Christiansen et al. (2004); Netherlands: Oenema and DeLaune (1988), Esselink et al. (1998); Temmerman et al. (2004); England: Allen (1991), Cahoon et al. (2000), French (1994); French and Burningham (2003), Harper (1979), Kestner (1975), Reed (1988); Brittany: Guilcher and Berthois (1957); northwest Portugal: Moreira (1992); USA: Harrison and Bloom (1977), Stevenson et al. (1986); excluding highly autochthonous marshes), Stumpf (1983). B) Plot of vertical balance (i.e. difference between rates of elevation change, E, and sea-level rise, M) against mean tidal range for sample of northwest European and North American allochthonous marshes. Vertical bars reflect range in reported sedimentation or elevation change rates within individual marsh systems.

Blackwater Marsh, a tidal freshwater system bordering Chesapeake Bay, USA (Stevenson et al., 1986), retained within the analysis on account of its extremely small mean tidal range (about 0.3 m). Elsewhere in Chesapeake Bay, more saline estuarine marshes appear to show a healthy excess of sedimentation over sea-level rise. Riverine marshes may well respond rather differently to sea-level rise than those subject to a stronger tidal influence. For example, Stevenson et al. (1986) note the larger contribution to vertical growth from autochthonous peat formation, and the potential mass degradation of peats that can occur following saline intrusion (see also, Howarth and Hobbie, 1982).

Not surprisingly, many marshes plot close to equilibrium with sea-level rise (i.e. $E-M=0$) although no marsh in the sample dataset has sedimentation and sea-level rise exactly in balance. Although variance in sedimentation increases with tidal range, for sites where spatially-distributed sedimentation or elevation change data are available, minimum rates tend to be nearly equivalent to sea-level rise (see, for example, French and Spencer, 1993). That a few individual measurements indicate an apparent elevation deficit with respect to sea-level rise is not unexpected given the difficulty in reconciling a few years of sedimentation data with sea-level trends inferred from noisy tide gauge records spanning several decades. Micro- and meso-tidal systems, in particular, are also likely to be more strongly influenced by storm events (see, for example, Stumpf, 1983). Under-representation of high magnitude events may also give rise to spurious elevation deficits, especially where data are obtained from infrequently flooded high or back-marsh locations.

Long-term monitoring of estuarine and coastal sediment dynamics generally reveals considerable variability in suspended sediment concentration (SSC), often over an order of magnitude and at multiple timescales (e.g. Ridderinkhof et al., 2000; Schoelhammer, 2002). Models of vertical marsh growth are typically calibrated using a hypothetical long-term ‘climatic’ mean concentration, and it is obviously hoped that the optimum concentration will lie well within the range of observed values for the site in question (e.g. Krone, 1987; French, 1993). Generalisation across a broad geographical sample of marshes based upon this level of data is less satisfactory, given that linkages between regional-scale sediment supply and that within the overmarsh water column are likely to be complex, yet remain poorly quantified. However, an attempt has been made to establish at least the envelope of SSC for as many as possible of the systems represented in Fig. 2, for which data allow a reasonable estimation of sediment inputs to the marsh surface. Indicative 'average' concentrations have been derived, either directly from the original studies or, in a few cases, as the mid-point of the published range.

The data reveal only weak linkages between vertical elevation balance and SSC (Fig. 3A) and between SSC and mean tidal range (Fig. 3B) but do at least provide some basis for the estimation of potential sediment supply. Irrespective of the limitations of the underlying data, the linkage between sedimentation and SSC is likely to be made more complex by variation in the efficiency with which sediment is trapped, both between marsh sites and over time as an individual marsh develops.

There is no clear trend in either gross sedimentation or net elevation balance with increasing tidal range. Instead, and in accordance with the conceptual model presented in Fig. 1, higher tidal ranges translate into a larger accommodation space available for infilling such that the potential range of sedimentation recorded is larger than for micro-tidal settings. This has implications

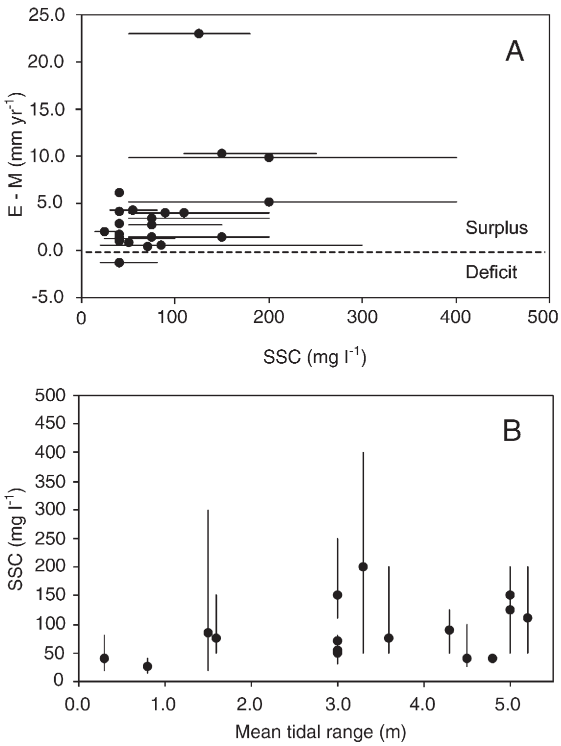

Fig. 3. A) Plot of vertical balance ($E-M$) against 'indicative' long-term mean suspended sediment concentration (SSC) for northwest European and North American allochthonous marshes. Horizontal bars indicated range of reported SSC from which indicative mean values are derived. B) Plot of indicative SSC against mean tidal range for northwest European and North American allochthonous marshes plotted in Fig. 3. Vertical bars reflect range in reported SSC within individual marsh systems.

for the response of established marshes to accelerated sea-level rise. An increase in the rate of sea-level rise will, in the absence of any change in sediment supply (or the efficiency with which the existing supply is sequestered), result in a lower equilibrium elevation relative to the tidal frame such that the rate of sedimentation remains high enough to offset the rise in sea-level. Accelerated sea-level rise is thus very likely to result in at least some increase in hydroperiod within tidal marshes, and this may be sufficient to force changes in ecosystem community structure (e.g. Warren and Niering, 1993; Chambers et al., 2003). Such systems are resilient, in that increased sedimentation will at least partly offset the potential increase in hydroperiod, and in that their ecosystem functions can be sustained across a broad vertical niche within the upper intertidal zone. However, this resilience cannot be inferred solely from comparison of sedimentation and sea-level rise but requires knowledge of the potential sediment supply available to drive higher rates of sedimentation given an increase in tidal hydroperiod. The dependence of marsh resilience upon tidal and sediment supply forcing, and the variation in sediment trapping efficiency, with relative elevation within the tidal frame, is investigated in the following section through exploratory numerical modelling.

3.2. Exploratory parameter space modelling

Fig. 4A shows modelled surfaces for vertical sedimentary balance (i.e. $E-M$, from Eq. (1)) for marshes with mean elevations at MHWN and MHWS. The horizontal plane corresponding to $E-M=0$ (equilibrium between sedimentation and sea-level rise) is also shown. The plot indicates the envelope of potential marsh sedimentation rate, as controlled by tidal range and sediment supply in the absence of any sea-level rise. Modelled sedimentation rates are broadly consistent with Fig. 2, although the highest reported sedimentation rates lie some way below the modelled upper limit of the envelope, as defined by MHWN. This probably reflects the fact that most saltmarsh monitoring programmes have been carried out in well-established marshes rather than low and recently-vegetated marshes.

Fig. 4B shows the effect of the imposition of sea-level rise at 2 mm a^{-1}. This is the mean sea-level rise for the sub-sample of marshes represented in Fig. 3: the locations of these marshes within the parameter space are also plotted, based upon their mean sedimentation and their approximate mean SSC. Most of the sample marshes lie on or below the modelled MHWS surface: none plot above the MHWN surface (which has been

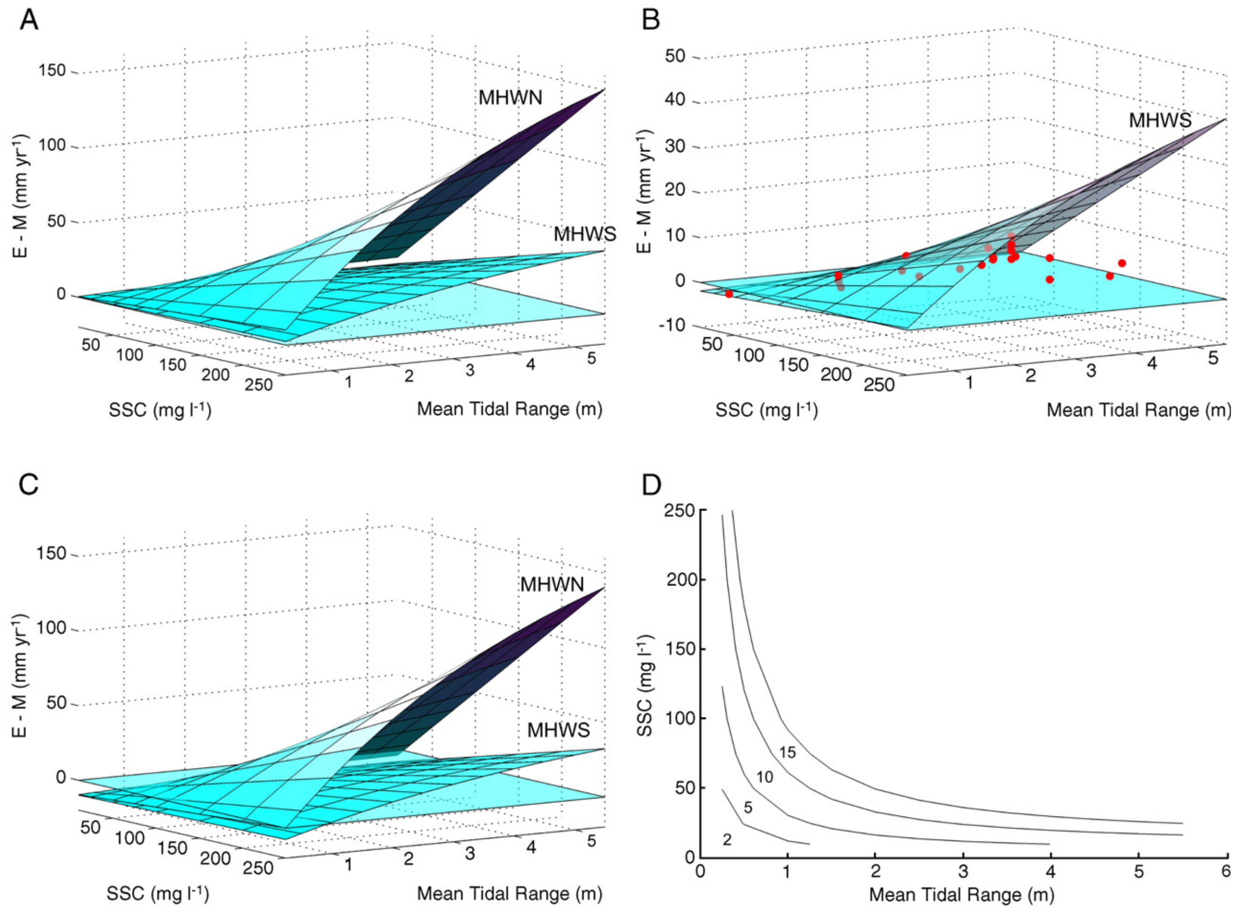

Fig. 4. A) MARSH-0D modelled vertical sedimentation balance ($E-M$) for marsh surfaces at MHWN and MHWS. B) modelled surface for MHWS only, with $M=2$ mm a^{-1} and sample data from Fig. 3 plotted. C) modelled vertical sedimentation balance ($E-M$) for marsh surfaces at MHWN and MHWS with $M=10$ mm a^{-1}. D) location within parameter space defined by tidal range and SSC of 'submergence' threshold at which $E-M=0$ for a marsh with a mean elevation equal to MHWN.

omitted from this plot for clarity). Again, this is consistent with the fact that the field data generally derive from well-established marshes, which are known to have mean elevations close to (and even slightly above) MHWS (see, for example, French and Reed, 2001).

With sea-level rise increased to 10 mm a^{-1} (Fig. 4C) the 'submergence' zone expands to encompass a broader range of meso-tidal systems with low sediment availability. Fig. 4D shows the extent of this submergence zone, for varying rates of sea-level rise. The area below the modelled curves defines regions in which projected sedimentation on a surface at MHWN is insufficient to maintain elevation against the indicated sea-level rise.

It is instructive to consider the implications of the above results in terms of the efficiency with which different marshes sequester the sediment introduced by tidal action. Within MARSH-0D, the vertical settling flux is constrained by the choice of particle settling velocity, w_s. Since w_s is represented as a constant, only the variation in efficiency with tidal range can be considered here. Fig. 5 shows the sediment retention for marshes lying at MHWN and MWHS for $w_s=1\times10^{-4}$ m s^{-1} (default used in the other simulations), $0.5\times10^{-}4$ m s^{-1} and 2.0×10^{-4} m s^{-1}. Sediment retention efficiency obviously increases with w_s and over time as marsh infills the tidal frame. Micro- and meso-tidal systems also appear to utilise a much higher proportion of the available sediment to maintain their elevations than do macro-tidal systems. Few field data exist to compare with these model outcomes. Gross marsh sediment budgets derived from tidal channel flux studies (e.g. French and Stoddart, 1992; Asjes and Dankers, 1994) are of limited value in this respect since they do not disaggregate sediment exchanges taking place

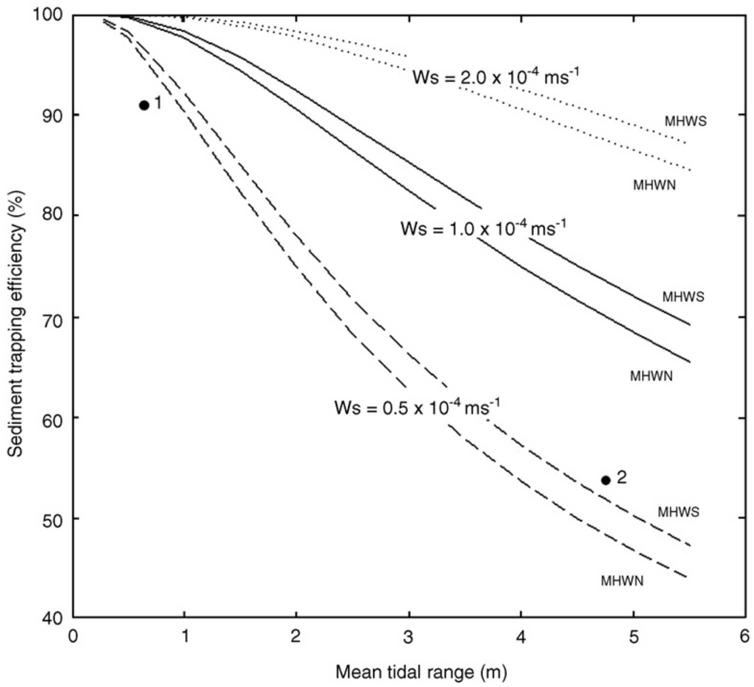

Fig. 5. Modelled sediment trapping efficiency (% of sediment introduced on flood tide retained on the marsh surface), for marshes at MHWN and MHWS as a function of mean tidal range, and particle settling velocity, w_s. Equivalent field data for (1) Holland Glade Marsh, Delaware, USA (Stumpf, 1983) and (2) Hut Marsh, Norfolk, UK (French, 1989) are also plotted.

across the interface between the channel margin and the marsh surface, and within-channel deposition and erosion. Of more relevance is the finding of Stumpf (1983) that around 80% of the suspended sediment within water inundating a small micro-tidal marsh in Delaware, USA, was lost from suspension within around 10 m of a major channel, and 90% for waters inundating marsh interior areas. In contrast, French (1989) estimated that the sediment trapping efficiency of a macro-tidal saltmarsh in Norfolk, UK, was about 54% (with a temporal variation of 30% to 79%). The observed decline in sediment retention efficiency at higher tidal ranges is consistent with the model results, although further inferences are limited by the simplistic representation of particle settling and by the lack of any re-suspension term.

3.3. Sensitivity to sea-level, hydroperiod and sediment supply

Whilst sedimentation (or elevation change) measurements provide a limited basis for assessment of marsh resilience to external sea-level or sediment supply forcing, they can usefully support studies of marsh sedimentary processes and the estimation of short-term sediment budgets. In this context, it is instructive to consider the temporal variability in sedimentation that may be expected in systems occupying different positions within the parameter space investigated in the preceding section. In the case of sea-level, an important source of variation exists due to the 18.6 yr nodal modulation of the lunar tidal constituents (Pugh, 1987). The impact of nodal variation on tidal sedimentation both modern (e.g. Oost et al., 1993) and ancient (e.g. Choi et al., 2001) is well established. With regard to saltmarsh sedimentation, only Allen (1990, 2000) has explicitly acknowledged the need to incorporate nodal effects, even if only through averaging of tidal hydroperiod over a 19 yr interval. More recently, Chambers et al. (2003) have drawn attention to the role of 19 yr hydroperiod variation in providing windows of opportunity for the expansion of *Phragmites australis* communities with tidal brackish marshes.

Fig. 6A shows the effect of nodal tidal variation on hydroperiod, sedimentation rate and the sediment retention efficiency for hypothetical macro-tidal and micro-tidal marshes, over a 100 yr period. Both sets of simulations assume a modest linear sea-level rise (M=2 mm a^{-1}), a long-term SSC (i.e. C_{flood}, in Eq. (1)) of 75 mg l^{-1}, and an initial elevation equivalent to MHWS. Tidal data are synthesised from M_2, S_2, K_1 and

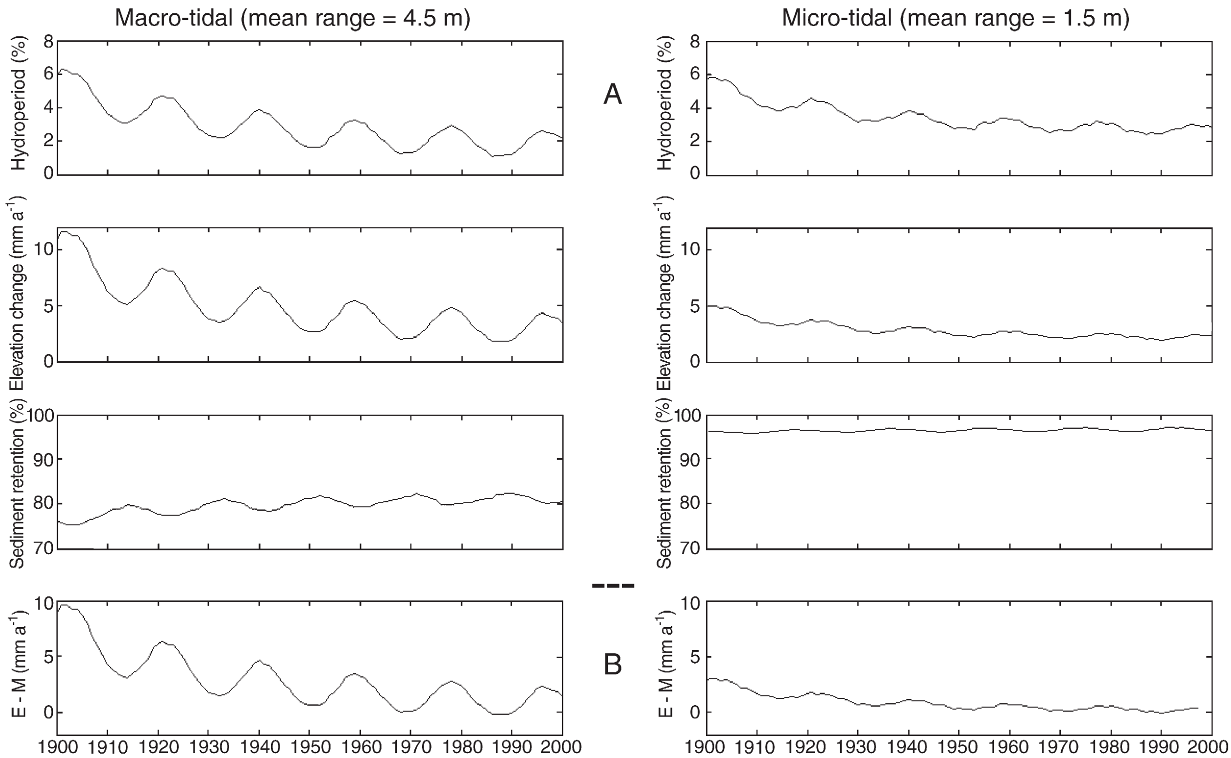

Fig. 6. A) Effect of 18.6 yr nodal tidal variation on hydroperiod, sedimentation rate and sediment retention efficiency for macro-and meso-tidal marshes, over a 100 yr period (M=2 mm yr^{-1}; SSC=75 mg l^{-1}). B) Variation in vertical sedimentary balance (i.e. $E-M$). Initial elevation in both cases is equivalent to MHWS. For explanation see text.

O_1 harmonic constituents (for convenience, these were taken for the UK east coast ports of Immingham and Lowestoft respectively), with nodal factors for the lunar constituents calculated in the manner of Pugh (1987). These simulations represent the idealised behaviour of well-established marshes that are approaching equilibrium within the tidal frame. In both cases, relatively small variations in tidal amplitude translate into rather larger variation in hydroperiod within the upper intertidal, which then force significant inter-decadal variability in sedimentation rate. Although purely indicative, these results do provide a further illustration (Fig. 6B) of how misleading comparisons of short-term sedimentation (averaged over a few years) and longer-term linear sea-level trends can be.

In addition to periodic tidal contributions, hydroperiod is also subject to various meteorological forcings. Static barometric pressure effects (Pugh, 1987) are easiest to handle, using the theoretical sea-level anomaly of -10 mm mb^{-1} (i.e. the so-called 'inverse barometer effect). Fig. 7 shows the additional effect of static pressure variation, based upon data for mean monthly sea surface pressure for 1900–2000 obtained from the Climate Research Unit at the University of East Anglia, UK (data obtained for 0° E, 50° N; for description see Basnett and Parker, 1997). The effect is small in the case of the macro-tidal system, but generates irregular fluctuations in sedimentation rate that are comparable in magnitude to the underlying nodal variation within the micro-tidal system. This is consistent with the finding that micro-tidal marshes tend to depend to a greater degree on infrequent storm-driven sedimentation for the maintenance of their elevations than their meso- and macro-tidal counterparts (e.g. Stumpf, 1983). In regions subject to strong dynamic surge effects, such as the southern North Sea, short-term variation in hydroperiod will, of course, be much larger, although its translation into interannual variation possibly rather less so. It is less practical to model dynamic surge variability given the lack of appropriate long-term data, and the highly idealised harmonic representation of the underlying tidal curves within these MARSH-0D simulations. Such an exercise could, however, be undertaken for case study marshes for which historic surge data are available.

Very few long-term datasets exist with which to test further the relation between various forms of sea-level

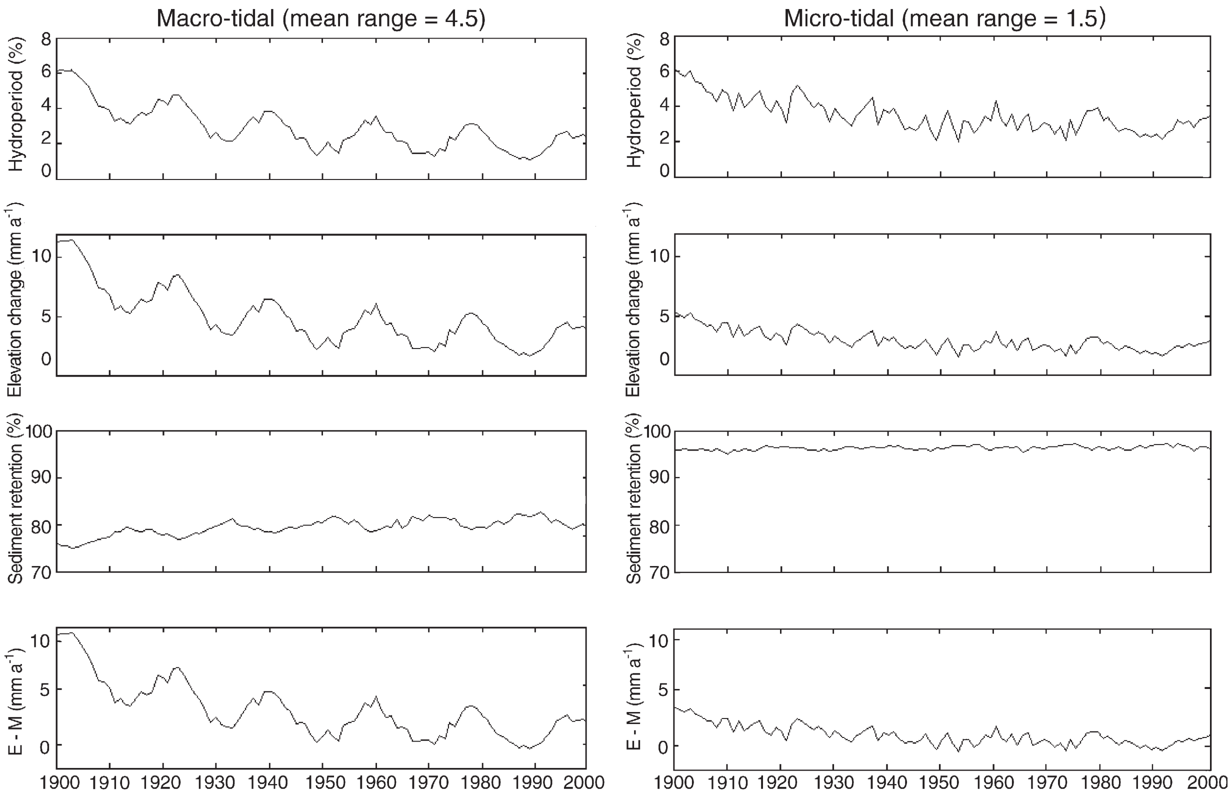

Fig. 7. Simulations as in Fig. 6, but with monthly static atmospheric pressure effect modelled. For explanation see text.

forcing and tidal marsh sedimentation. An exception is the detailed work undertaken at Skallingen, in the Danish Wadden Sea (Nielsen and Nielsen, 2002; Bartholdy et al., 2004). At this micro-tidal location, the frequency and magnitude of marsh inundation events is strongly influenced by the strength and frequency of westerly winds. Intriguingly, Bartholdy et al. (2004) identify a strong correlation between annual sedimentation (determined by a semi-empirical model) and the North Atlantic Oscillation (NAO) winter index (Jones et al., 1997), a climate measure based on the pressure gradient between Lisbon (Portugal) and Iceland (Stykkisholmur). High values of the NAO winter index imply ideal conditions for strong Atlantic westerlies and these are linearly associated with higher rates of deposition within the backbarrier marsh at Skallingen. The range of mean annual sedimentation on the marsh transect studied was approximately 0.8 to 4.5 mm a^{-1} for the period 1970 to 1999.

For illustrative purposes, Fig. 8 shows sedimentation rates for SSC of 38, 75 and 150 mg l^{-1} superimposed upon the scenarios given in Fig. 7. One would expect this kind of variability in both sea-level and hydroperiod to be associated with changes in sediment concentration within waters inundating the marsh surface. Only a few localities are well enough documented with respect to suspended sediment dynamics to allow this interaction to be modelled. One such case is the Scheldt estuary, southwest Netherlands, where long tidal records have been supplemented by intensive suspended sediment monitoring campaigns. At two marsh sites within the Scheldt, Temmerman et al. (2003, 2004) observed a statistically significant positive relationship between individual High Water (HW) levels and the suspended sediment concentration of water entering the marsh surface on the flood tide. Any such relationship will have the effect of accentuating the temporal variability in sedimentation produced by hydroperiod variations alone. However, the coefficient of proportionality varied by a factor of 4 along a 120 km estuarine transect, mitigating against generalisation at a regional scale. Within a macro-tidal backbarrier saltmarsh in Norfolk, UK, French (1989) found no significant relation between HW level and SSC (though the number of tides sampled was much smaller).

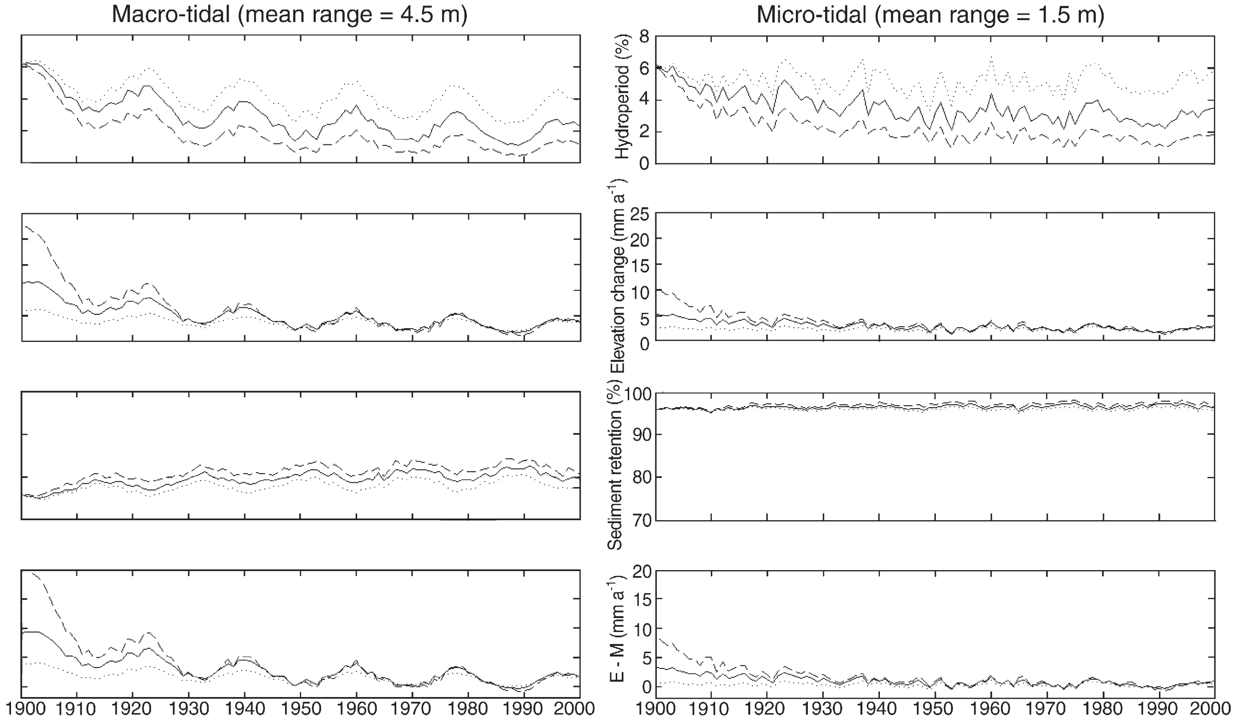

Fig. 8. Simulations as in Fig. 7, but with variation in sediment supply modelled: curves represent SSC=38 mg l^{-1} (…); 75 mg l^{-1} (solid line); and 150 mg l^{-1} (---).

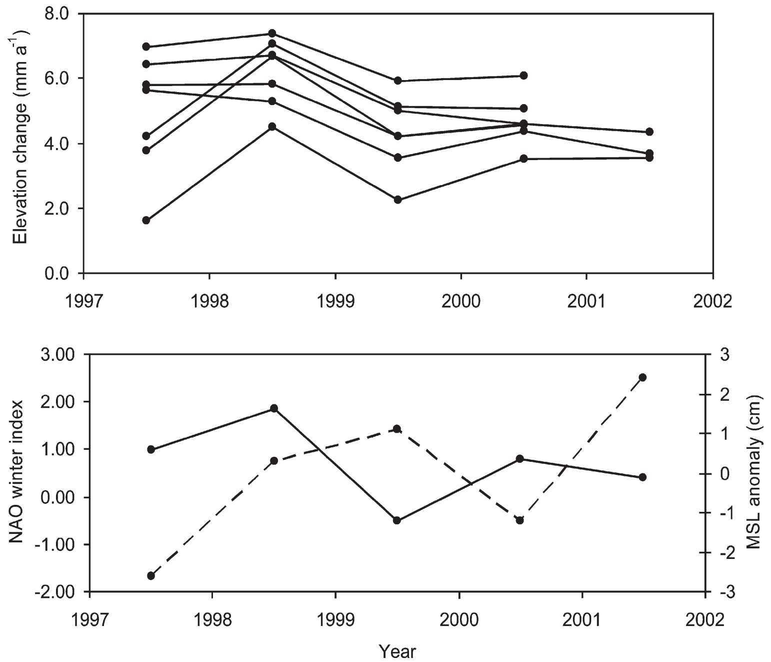

Fig. 9. A) Measured elevation change for 7 estuarine saltmarsh sites (within two distinct marshes) in the Blyth estuary, Suffolk, UK (data from French and Burningham, 2003); B) NAO winter index (solid line; source: Climate Research Unit, University of East Anglia, UK) and (dashed line) mean sea-level anomaly relative to 1997–2002 mean (data for Lowestoft, Suffolk, UK: UK Permanent Service for Mean Sea-Level).

It is difficult, therefore, to disaggregate the contributions of varying sea-level, hydroperiod and sediment supply to time variation in marsh sedimentary response. Sea-level and hydroperiod effects are more readily modelled, but sediment supply variation may be of equal or greater importance in some locations. Again, data are sparse, but one location where this appears to be the case is the micro-tidal Blyth estuary (Suffolk, UK). French and Burningham (2003) document coherent estuary-wide interannual variation in both sedimentation rate and net elevation change within well-established saltmarshes fringing the subtidal channel of the Blyth (Fig. 9). This variability in sedimentation does not correlate with either mean sea-level or hydroperiod, but a direct association with the NAO winter index is evident. French et al. (2005) show a linkage between strong westerly wind events and elevated suspended sediment concentrations due to wave re-suspension over the extensive mid-estuary mudflats. If sea-level and hydroperiod are not the mechanism driving variation in sedimentation within such allochthonous marshes then, by implication, sediment supply modulation by local meteorological events must be the dominant factor. As yet, the data series is short, and a longer record is required to fully substantiate the NAO–wave action–sedimentation linkage implied by the above results.

3.4. Effect of autocompaction on allocthonous marsh depositional sequences

After incorporation into the marsh sedimentary sequence, muddy sediments undergo volume reduction through autocompaction. Two distinct sets of processes are recognised within the geotechnical literature (Audet, 1995): first, time-dependent *consolidation* due to the expulsion of pore fluid as the sediment structure

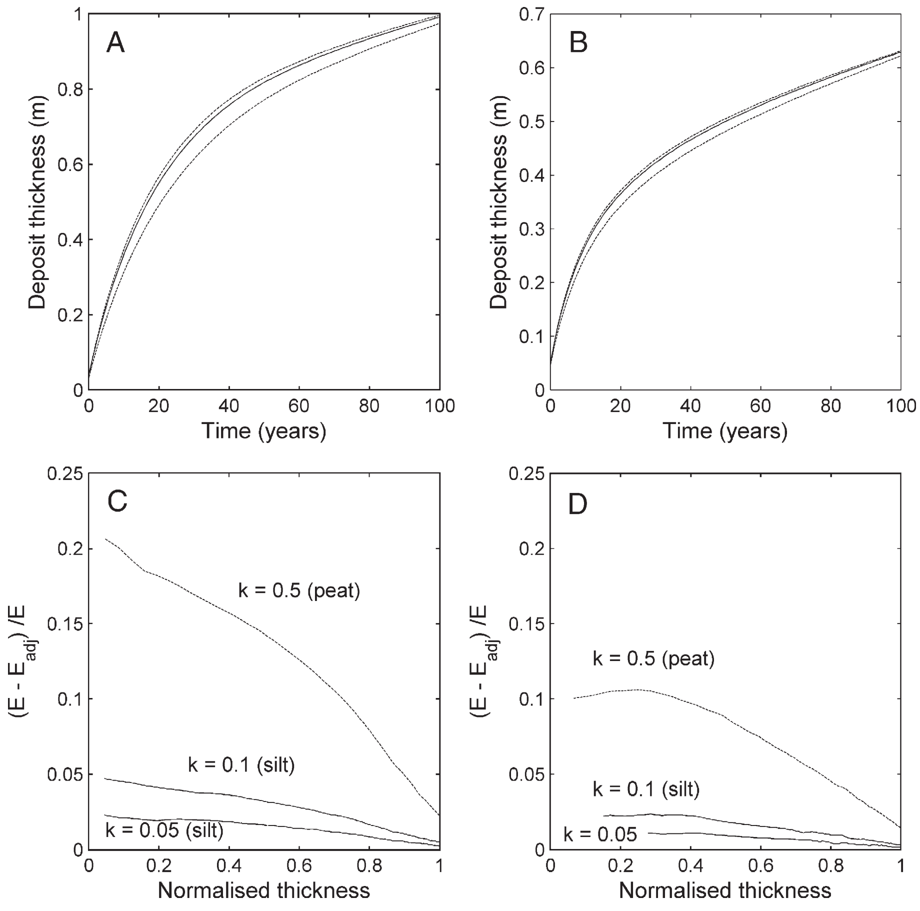

Fig. 10. Effect of autocompaction on modelled elevation curves (upper broken line = no compaction; solid line; k=0.1; lower broken line: k=0.5) for hypothetical macro-tidal (A) and micro-tidal (B) marshes (other parameters as in preceding simulations). Curve for k=0.05 curve is virtually indistinguishable from no-compaction case and is omitted for clarity. Plots C and D show relative elevational lowering for macro-tidal © and micro-tidal (D) systems, for different values of k. In all cases, SSC=150 mg l^{-1} and M=2 mm a^{-1}.

approaches equilibrium with the applied load; second, *compression*, as the equilibrium volume is reduced with an increase in applied stress (here, due to the increasing overburden of continuing sedimentation). Gibson (1958) showed that the time-dependent contribution need be considered only in the case of extremely high rates of deposition. With the exception of the near-surface layer (where dehydration processes are more active), therefore, highly allochthonous marsh deposits are fully consolidated.

Within allochthonous sequences compression effects are also likely to be small, certainly in comparison with peat-dominated sequences. This is consistent with vertical bulk density profiles (e.g. French, 1989; Callaway et al., 1996) which often show only a slow, near-linear, increase with depth below the rooting zone. Analysis of numerous profiles from the UK suggests that a value of $k \approx 0.05$ to 0.10 is reasonable for the compressibility coefficient in Eq. (3). In comparison, Allen (1999) found that $k \approx 0.04$ for deep Holocene silt sequences in the Severn estuary, with $k \approx 0.50$ for peat sequences.

The effects of including autocompaction based upon the compression model of Eq. (3), with $k=0.10$, are presented in Fig. 10. Fig. 10A, B show (for macro- and meso-tidal settings respectively) the small effect of realistic allochthonous sedimentation ($k \leq 0.10$) compared to that for marsh peats (described here by $k=0.5$). Model results also show (Fig. 10C, D) that autocompaction negates the translation of sedimentation into elevational gain most strongly around the middle of the depositional history as early depositional increments are thinned by continuing sedimentation. But as equilibrium with sea-level rise is asymptotically approached, autocompaction effects become of negligible importance.

4. Discussion

The predominantly allochthonous tidal marshes analysed in this study show rates of sedimentation sufficient to drive continued vertical infilling of the intertidal accommodation space despite widely varying rates of sea-level rise. Although there are no instances where sedimentation and sea-level rise appear to be exactly in balance, micro-tidal marshes generally lie close to this hypothetical equilibrium state. An example is the backbarrier marsh at Barn Island, Connecticut (mean tidal range 0.8 m), investigated over more than a decade by Harrison and Bloom (1977). Subsequent work by Orson et al. (1998) at this site shows a good correspondence between sedimentation and sea-level rise at 20 to 50 yr timescale, but only a weak correspondence between interannual sea-level and sedimentation variability. Storm effects that are largely unrelated to mean sea-level clearly play a particularly significant role in mediating allochthonous sedimentation within micro-tidal settings (see also, Stumpf, 1983; Roman et al., 1997).

The fact that most marshes show significant excess vertical sedimentation may, in part, be a consequence of spatial variation in sedimentation associated with topographically controlled on variation in hydroperiod (i.e. frequency and duration of tidal inundation). As the marsh builds vertically, one would intuitively expect the range of sedimentation rates to diminish, and a larger proportion of the upper marsh to achieve an elevation close to that at which equilibrium between sedimentation and sea-level rise prevails. However, the mean elevation and sedimentation rate for the marsh as a whole will approach this equilibrium condition over a very long time period, possibly of the order of 10^2 to 10^3 yr (French, 1993). The evolution of topography is most readily documented within backbarrier marshes, where marsh sediments typically comprise a thin veneer over stratigraphically distinct gravels and sands, and there is empirical evidence for declining landward gradients and a reduction in sedimentation variance as marshes accrete vertically (e.g. French and Reed, 2001; Nielsen and Nielsen, 2002; Bartholdy et al., 2004).

Local stratigraphic factors may also contribute to the vertical adjustment of marsh surfaces. Allen (1999), for example, has convincingly demonstrated the importance of autocompaction within Holocene coastal sequences as a factor modifying marsh topography and, significantly, enhancing short-term rates of sedimentation. Autocompaction is likely to be less important in thin backbarrier marsh sequences (e.g. Harrison and Bloom, 1977; Bartholdy et al., 2004), and precise measurements of actual elevation change in highly allochthonous backbarrier, coastal and estuarine marshes in the UK (Cahoon et al., 2000; French and Burningham, 2003) sedimentation and elevation change to be nearly equivalent, at least at a timescale of a few years. Where the Holocene stratigraphy is deeper and more complex, autocompaction of intercalated peat beds may contribute significantly to the enhancement of contemporary allochthonous sedimentation. In the Blyth estuary (Suffolk, UK), for example, this may well explain why apparently mature marshes with nearly horizontal surfaces marginally above MHWS continue to show rates of elevation change averaging 4.4 mm a^{-1} over a 4 to 5 yr timescale, well in excess of post-1956 sea-level rise averaging 2.4 mm a^{-1} (French and Burningham, 2003; French et al., 2005).

The points above relate chiefly to the interpretation of short-term sedimentation rates in the context of existing sea-level rise. A more important issue concerns the inappropriateness of treating a short-term sedimentation deficit or surplus as a measure of marsh vulnerability to a future acceleration in the rate of sea-level rise. Such comparison ignores the complexity of the interaction between elevation, hydroperiod and sedimentation (as summarised in Fig. 1). Whilst there is clearly scope for empirical work to establish the natural limits to past marsh response, modelling of some kind is required to elucidate more fully the non-linear nature of these linkages. Exploration of the parameter space defined by marsh elevation, sedimentation, sea-level rise, sediment supply and tidal range, using a zero-dimensional mass balance model provides insights into marsh morphodynamic behaviour beyond those obtained from monitoring alone.

The parameter space modelling presented in this paper provides at least a first order estimation of the natural limits to sedimentation, as constrained by tidal and sediment supply forcing, and the relative elevation of a marsh within the tidal frame. The envelope of potential sedimentation (Fig. 4A) is approximated by a region between a surface representing sedimentation at MHWN and that where sedimentation is equal to sea-level rise (which, for a stable sea-level, corresponds to a surface elevation equivalent to the Highest Astronomical Tide). Acknowledging the complex ecological transitions that are known to accompany significant changes in hydroperiod (e.g. Warren and Niering, 1993), a crude 'submergence' threshold can be defined as the line along which the balance of sedimentation on the MWHN surface becomes negative. As expected, the size of this region grows along the sediment supply and tidal range axes as the rate of sea-level rise increases (Fig. 4C). The resilience of tidal marshes to sea-level rise thus increases with tidal range and sediment supply. It is instructive to note the implied variation in marsh sediment retention efficiency between micro-tidal systems, which utilise virtually all of the available allochthonous sediment supply in the maintenance of their elevation, and macro-tidal systems, which utilise a much smaller fraction.

It is also interesting to consider the modelled temporal variability in marsh sedimentation and elevation balance with both 18.6 nodal tidal modulation and short-term meteorologically-forced variation in sea-level level. Nodal tidal effects, although often identified in the analysis of tide gauge records (e.g. Harrison and Bloom, 1977) have rarely been associated with time-variation in marsh sedimentation, presumably because few marsh monitoring programmes have extended over more than a few years in duration. However, exploratory modelling (Fig. 6) shows that under higher tidal ranges, sedimentation rates could vary substantially, with excess sedimentation relative to sea-level rise ranging from near zero to several mm a^{-1} over less than a decade. Meteorological effects largely mask these cycles in micro-tidal marshes (Fig. 7). Dynamic surge events, which are not modelled here, undoubtedly impart additional interannual variability in meso- and macro-tidal systems, especially in regions such as the southern North Sea (French and Reed, 2001).

Limited data availability means that only indicative insights can be obtained into marsh sensitivity to sediment supply. The effect of an increase in background SSC is to decrease the hydroperiod, since sea-level rise can be offset by more rapid sedimentation driven by fewer inundation events. A similar result was obtained by Temmerman et al. (2004), who showed that a 50% reduction in sediment supply could force a reduction in marsh level by 0.27 m in the meso- to macro-tidal marshes of the Western Scheldt estuary.

In highly allochthonous marshes, where depositional sequences are formed chiefly of marine silts and clays, autocompaction is of less importance with regard to the adjustment of the oldest marsh surfaces to continued external sea-level or sediment supply forcing. Whilst a variety of near-surface processes (including shrink-swell effects of the kind documented by Nuttle et al., 1990) undoubtedly complicate the linkage between sedimentation and elevation change, longer-range compression (the 'shallow subsidence' of Cahoon et al., 1995) is probably of limited importance within this kind of system. However, as Temmerman et al. (2004) have observed, some representation of compaction is useful for detailed reconstruction of sedimentation histories at sites for which the necessary data are available. Compaction is of much greater importance in *developing* marshes, where early elevational gain can be significantly negated, and, is clearly a much more important factor influencing the post-depositional behaviour of autochthonous marsh peats (Cahoon et al., 1995).

The analyses presented here are restricted to predominantly allochthonous tidal marshes, which occupy a range of physical settings that is broad enough to accommodate a variety of morphodynamic responses to both extrinsic and intrinsic forcing. The analysis focuses on marsh elevation as a system state variable that is of diagnostic value in terms of the linkages depicted in Fig. 1. This behaviour can be conceptualised using relatively simple models that provide a framework for the identification of those systems most vulnerable to environmental change. Actual marsh morphodynamic responses are more complex, encompassing lateral progradation/retreat and/or spatial translocation (e.g. in response to sea-level rise). Detailed case studies thus require models that incorporate a fuller set of ecological as well as physical processes and/or allow the prediction of spatially-distributed responses.

5. Conclusions

This overview shows that highly allochthonous tidal marshes do not exhibit as close a correspondence between sedimentation and sea-level rise as is often assumed. Although infilling of the tidal accommodation space results in marsh elevations that tend towards equilibrium with sea-level rise, the asymptotic nature of this process means that disequilibrium prevails within most tidal marshes.

Neither are sedimentation measurements, in themselves, diagnostic of the resilience of tidal marshes to external environmental changes such as an increase in the rate of sea-level rise. Instead, marsh behaviour is conditioned by a complex interplay between the elevation of the marsh surface, sedimentation, sea-level rise, sediment supply and tidal range. Exploratory modelling using aspatial mass balance schemes can provide approximate limits to sedimentation and highlight the differing sensitivity of marshes subjected to varying combinations of sea-level, tidal and sediment supply forcing. Although such models rely on fairly crude assumptions, they do constitute a framework for more intensive analysis of individual case study systems and serve to re-focus priorities for field-based research. In particular, it is argued that studies of marsh response to accelerated sea-level rise should focus not on measures of net sedimentary balance but on the estimation of sediment supply, and the efficiency with which this is depleted by deposition, as a quantifiable metrics of marsh resilience. This implies a shift towards more intensive process studies aimed at elucidating more fully the linkages between tidal marshes and adjacent estuarine and coastal systems.

Model results also highlight the significant variability in marsh sedimentation associated with 18.6 yr tidal modulation and meteorological processes at short-term scales. Such variability further complicates the interpretation of sedimentation or elevation change data obtained from monitoring programmes of short duration. Longer-term monitoring remains of value, however, as a means of identifying important mechanisms of climate and sediment supply forcing that may contribute to the formation and maintenance of marsh sedimentary sequences.

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