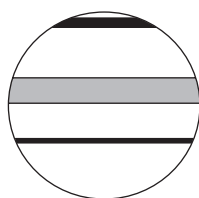


The application of local and regional transfer functions to the reconstruction of Holocene sea levels, north Norfolk, England

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Abstract: Foraminiferal assemblages from Thornham and Brancaster marshes (Norfolk, UK) illustrate statistically significant relationship with elevation with respect to the tidal frame. We develop local (data from Thornham and Brancaster marshes) and regional (data from Thornham and Brancaster marshes combined with those from 11 other sites around the UK) predictive foraminifera-based transfer functions to reconstruct former sea levels from a Holocene sediment sequence from Holkham, north Norfolk, UK. The two transfer functions produce similar patterns of tidal elevation change during the Holocene. The vertical error ranges of the local transfer function are smaller than those of the regional transfer function, although the difference (0.09 m) is not significant when compared to other factors affecting the reconstructed elevation. The value of the reconstructed elevations also differ between the two transfer functions (by up to 0.43 m), and this is primarily due to the lack of modern analogues in the local transfer function. We conclude that the reconstructions derived from the regional transfer function are more reliable than those of the local transfer function, since the latter achieves its slight increase in precision at the expense of a significant decrease in predictive power. The regional transfer function is used to construct a relative sea-level curve from fossil assemblages within a sediment core from north Norfolk, UK. These results are consistent with existing sea-level data and geophysical model predictions, and illustrate the utility of the foraminifera-based transfer function approach.

Key words: Sea-level change, tidal marsh, foraminifera, transfer function, Holocene, north Norfolk.

Introduction

A major issue in palaeoenvironmental studies is to understand how small-scale relative sea-level (RSL) changes are manifest in coastal sedimentary sequences. The currently available geophysical models of RSL changes (e.g., Peltier *et al.*, 2002) do not capture this type of submillennial-scale variability. Furthermore, the traditional methodologies used to investigate Holocene sea-level movements are often inappropriate for constructing high-resolution sea-level records. These traditional approaches rely on the identification and analysis of stratigraphic boundaries between terrestrial freshwater sediments and littoral facies (e.g., Shennan and Horton, 2002), which are unevenly distributed in space and time, and largely absent from many Holocene sequences (Edwards,

2001). This reliance on such small portions of the sedimentary record severely restricts the resolution at which changes may be examined.

Recent methodological developments, however, offer the potential for high-resolution sea-level reconstruction through the identification of small-scale biostratigraphic changes from intertidal sedimentary sequences. Such developments can be achieved because microfossil taxa (e.g., foraminifera) have restricted distributions in the intertidal zone and are therefore indicators of particular coastal sedimentary facies and tidal levels (e.g., Scott and Medioli, 1980). Recent research has provided empirical information regarding the intertidal distributions of diatoms, foraminifera and thecomebians and their relationships with sea level (e.g., Zong and Horton, 1998; Horton *et al.*, 1999a; Gehrels, 2000; Gehrels *et al.*, 2001; Edwards *et al.*, 2004). These relationships have been quantified in a series of transfer functions that have been used to derive quantitative predictions of tidal-level and Holocene sea-level

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history from microfossil assemblages (Horton *et al.*, 1999b; Zong and Horton, 1999; Gehrels, 2000; Edwards, 2001).

In this paper, we present a new record of Holocene sea-level change from Holkham, north Norfolk, UK, produced using a foraminifera-based transfer function (FBTF). We use this record to explore an important issue relating to the reliable development and application of intertidal FBTF. We examine the significance of the sampling strategy used to determine the modern foraminiferal distributions that form the basis of the transfer function reconstructions. We compare the performance of a FBTF derived from samples collected in the study area (FBTF_{local}), with one comprising surveys from a range of sites around the UK (FBTF_{regional}), to investigate the most appropriate spatial scale at which modern analogues should be compiled.

Study area

Local training sets of modern distributions of foraminifera and fossil core material were collected from Thornham and Brancaster marshes, and Holkham, respectively, on the north Norfolk coast (Figure 1). These field sites were selected to meet the objectives of the Land-Ocean Evolution Perspective Study (LOEPS) of the Land-Ocean Interaction Study (LOIS)

Special Topic 32, namely (a) to define the regional sedimentary framework and establish the Holocene sedimentary evolution of the north Norfolk coast and (b) to determine rates of environmental change and help predict future coastal change during periods of sea-level rise (Andrews *et al.*, 2000).

The coastline is composed of a suite of Holocene depositional environments, which appear to have little direct relationship with the underlying solid geology (Orford *et al.*, 2000). The resultant landforms of the north Norfolk coast are the result of Holocene sedimentation seaward of a preglacial coastline, the degraded form of which is visible along the landward margins of Thornham Marsh. Chalk cliffs occur at Hunstanton (mid-Cretaceous Carstone, Red Chalk and Lower Chalk) and at Weybourne (Upper Chalk) where they are mantled by Quaternary glacial deposits. The chalk is overlain by Quaternary glacial till or fluviglacial sands and sandy-gravels, which is itself further overlain by accumulations of freshwater peats, the result of Holocene sea-level rise that apparently impeded coastal drainage and elevated groundwater levels (Funnell and Pearson, 1989). The freshwater peats were later progressively inundated and overlain by transgressive marine deposits. In numerous locations, a succession from intertidal muds through salt marsh deposits is apparent with freshwater peats accumulating on top of the higher marsh deposits.

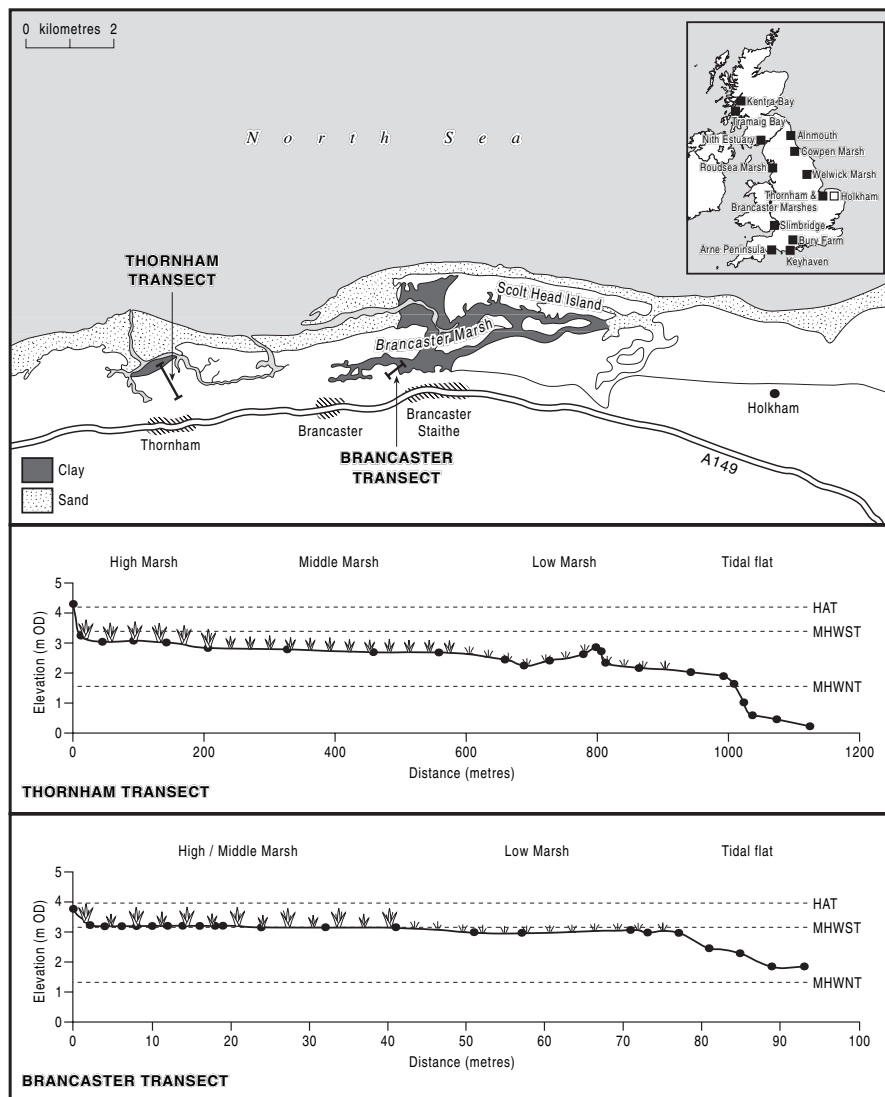


Figure 1 Map of the north Norfolk coastline. Inset: map of the UK, showing study modern (black square) and fossil (white square) field sites.

Table 1 Tide levels for Thornham and Brancaster marshes (source: Admiralty Tide Tables, 2002)

Site	Lowest astronomical tide (LAT)	Mean low water spring tide (MLWST)	Mean low water neap tide (MLWNT)	Mean sea level (MSL)	Mean high water neap tide (MHWNT)	Mean high water spring tide (MHWST)	Highest astronomical tide (HAT)
Thornham	-3.85 m OD	-3.15 m OD	-1.55 m OD	0.10 m OD	1.55 m OD	3.35 m OD	4.15 m OD
Brancaster	-4.09 m OD	-3.39 m OD	-1.79 m OD	-0.14 m OD	1.31 m OD	3.11 m OD	3.91 m OD

The modern low-lying barrier coast of north Norfolk is today being shaped by a macro to macrotidal regime (6.0 m at spring tides and 3.1 m at neap tides; Table 1; Admiralty Tide Tables, 2002). However, because of the water is relatively shallow offshore, wave energy is low to moderate with an average wave height at Scolt Head Island of 0.2 m to 0.3 m (Pye, 1992; Andrews *et al.*, 2000). The high tidal range and shallow gently inclined offshore slope has produced extensive intertidal sand and mud, but a number of salt marsh units have developed in the lee of complex, recurved shingle barriers (Funnell and Pearson, 1989).

The apparent impact of human activity on the natural evolution of the north Norfolk coast has been minor, at least in comparison with estuarine marshes of the UK (e.g., Cowpen and Welwick marshes). From the time of the early Roman settlements (e.g., Branodunum; now Brancaster) trade flourished from numerous small harbours including those at Thornham, Brancaster, Burnham Overy and Wells. However, changing patterns of trade, together with the siltation that accompanied the growth of the salt marshes, ultimately led to the decline of these harbours with only Wells now surviving (Allison, 1985).

Thornham Marsh is approximately 1 km wide and can be divided into high, middle and low marsh on the basis of the vascular flora. The high marsh is dominated by *Spergularia marina*, *Puccinellia maritima* and *Elytrigia atherica*. The number of species increases at the transition between high and middle marsh, with the latter dominated by *E. atherica*, *Atriplex portulacoides* and *Limonium vulgare*. The transition to the low marsh is marked by a decrease in the number of species with only two remaining (*A. portulacoides* and *Salicornia europaea*). The low marsh possesses a variable microtopography associated with ridge and runnel sand bars.

Brancaster Marsh lies in the lee of Scolt Head Island, which is a natural, dune-covered shingle barrier (e.g., French *et al.*, 1990; Andrews *et al.*, 2000). It can be divided into a high/middle and low marsh, with the former having the greatest number of floral species (dominated by *Phragmites australis*, *Plantago maritima* and *Armeria maritima*) and the latter dominated by *Spartina* spp., *A. portulacoides*, *Inula crithmoides* and *S. europaea*. The middle and low marsh possess a variable microtopography formed by creeks, levees and pools.

A sediment core for fossil analysis was recovered from Holkham (NCC17). The coastal geomorphology of the Holkham area consists of prograding sandflats and vegetated aeolian dune ridges which are fronted 500 m seawards by a foredune ridge along the beach platform with embryonic salt marshes forming behind (Andrews *et al.*, 2000).

Methods

Modern samples

Foraminiferal and environmental samples (elevation, pH, salinity, substrate and vegetation cover) were collected from cross-marsh transects covering tidal flat to high marsh, close to or above highest astronomical tides. The sample stations were placed at marked changes in topography and encompass a wide

variety of ecological communities. All stations were surveyed to Ordnance Datum (OD, Newlyn – the UK national levelling datum) using a level and staff. Two samples were collected at each station: one sample of approximately 10 cm³ volume (10 cm² surface sample by 1 cm thick) for foraminiferal analysis; and a second sample of approximately 30 cm³ volume (30 cm² surface sample by 1 cm thick) for environmental analysis. The foraminifera of Thornham and Brancaster marshes were sampled four times during a 12-month period (once in each season) and expressed as an annual average. Horton and Edwards (2003) concluded that an investigation of contemporary salt marsh foraminifera that recovers a complete set of samples in the winter, spring, summer and autumn (i.e., four samples per year) will provide the best-quality data for use in sea-level investigations. However, the environmental variables were only collected once during a 12-month period; thus, all variables, except elevation, are susceptible to seasonal variations as the result of changes in the balance between seepage, precipitation and flooding (de Rijk, 1995; Horton, 1999).

Foraminiferal sample preparation and taxonomy follows Scott and Mediolli (1980) and Horton (1999). Modern samples were stored in buffered ethanol with the protein stain Rose Bengal added to identify organisms living at the time of collection (Walton, 1952; Murray and Bowser, 2000). Foraminiferal analyses of the modern samples uses the death assemblage because it is relatively unaffected by the seasonal fluctuations apparent in life assemblages and shows only minor variations between subsurface and surface samples (Horton, 1999; Horton and Edwards, 2003). Foraminifera preservation was generally good in both modern and fossil deposits. A minimum count of 300 tests was performed for most samples (following Patterson and Fishbein, 1989) and species that reach 2% of the total sum are included in any statistical analysis.

Core collection

A programme of coring was conducted in the vicinity of Holkham. Shell and auger percussion cores were recovered in 1 m long rigid plastic liners and sediments were used for sedimentological, lithofacies and biofacies studies. Details of the site, stratigraphy and results have been published in Andrews *et al.* (2000).

Here we use foraminiferal assemblages sampled from core NCC-17 of Andrews *et al.* (2000). The chronological framework for the core is provided by four radiocarbon ages and five infrared stimulated luminescence ages (IRSL). Samples for luminescence dating were taken from opaque core liners under subdued red light and sealed in black plastic containers to preserve water content (Andrews *et al.*, 2000). Andrews *et al.* (2000) obtained the ages via the age equation in its simplest form:

$$\text{Luminescence age} = \frac{\text{palaeodose}}{\text{annual dose}} \quad (1)$$

Evaluation of palaeodose and annual dose was determined via the analytical techniques of Bailiff and Tooley (2000). We

Table 2 Chronology for Holkham NNC17 (modified from Andrews *et al.*, 2000)

Method	Laboratory code/ sample reference	Elevation (m OD)	¹⁴ C/IRSL age (yr BP)	Calibrated age range (BP)		
				Max.	Mid.	Min.
IRSL	NNC-17-3	0.54	2300 ± 200	2700	2325	1950
IRSL	NNC-17-2	-1.44	2800 ± 200	2920	2670	2420
Radiocarbon	AA22707	-1.61	2715 ± 70	3000	2870	2740
IRSL	NNC-17-5	-2.94	4700 ± 400	5050	4350	3650
IRSL	NNC-17-6	-3.00	4500 ± 400	5450	4750	4050
IRSL	NNC-17-4	-4.88	5700 ± 700	6450	5500	4550
IRSL	NNC-17-1	-6.10	5900 ± 600	6850	6000	5150
Radiocarbon	AA22681	-6.36	5930 ± 100	7050	6775	6500
Radiocarbon	AA23465	-6.53	6375 ± 60	7480	7315	7150
Radiocarbon	AA22682	-6.70	7760 ± 95	8950	8650	8350

calibrated the radiocarbon data using the Intcal98 calibration curve (Stuiver *et al.*, 1998) and combined with the IRSL ages and associated stratigraphic information using OxCal (version 3.5: Bronk Ramsey, 1995; 1998). The resulting sequence of ages (Table 2) was interpolated to produce the general accumulation history used to temporally constrain the variations in mean sea level identified from the foraminiferal data.

Transfer functions

Foraminifera-based transfer functions have been developed using a unimodal-based technique known as weighted averaging partial least squares via the program CALIBRATE, release 0.70, 1997 (Juggins and ter Braak, 1997). The local transfer function uses the modern foraminiferal and environmental data from Thornham and Brancaster marshes. The regional transfer function combines the former information with data from 11 other intertidal zones from sites around the UK coast (Figure 1; Table 3). This regional training set contains a wide range of modern coastal environments and includes data from three new sites, and thus is larger than those employed in previous UK studies (Horton *et al.*, 1999b; 2000; Edwards and Horton, 2000).

Although the regional transfer function has more samples, both data sets cover a similar range of intertidal heights. For the local and regional FBTFs; the position of each sample relative to the local tidal frame is of interest, thus, sample elevations must be normalized to account for intersite differences in tidal conditions. This is achieved by converting the

elevation of each sample to a standardized water level index (SWLI):

$$x_{ab} = [(A_{ab} - \text{MLWST}_b) / (\text{MHWST}_b - \text{MLWST}_b) \times 100] \quad (2)$$

where x_{ab} is the SWLI of station or tide level a at site b ; A_{ab} is the measured elevation (m OD) of station or tide level a at site b ; MLWST_b is the mean low water spring tide level at site b (m OD); and MHWST_b is the mean high water spring tide at site b (m OD).

The matching analogue technique (MAT) is an important means of evaluating the likely reliability of environmental reconstructions based on the local and regional transfer functions. The technique compares numerically, using an appropriate dissimilarity or similarity coefficient, the biological assemblage in a fossil sample with the biological assemblages in all available modern samples that have associated environmental data. Having found the modern sample(s) most similar to the fossil sample, the fossil environment for that sample is inferred to be the modern environmental variable(s) for analogous modern sample(s) (Birks, 1995). The 10th percentile of the dissimilarity range calculated between modern samples is an approximate threshold value to indicate a 'good analogue' (Bartlein and Whitlock, 1993; Birks, 1995; Edwards and Horton, 2000; Horton *et al.*, 2000). Thus, the reconstructed SWLI for sample i was assumed to be reliable if a 'good analogue' (dissimilarity coefficient < 10th percentile) was indicated while the estimates associated with 'no close analogue' (dissimilarity coefficient \geq 10th percentile) samples should be treated with caution. The matching analogue technique was developed using the program MODERN ANALOGUE TECHNIQUE, release 1.1 (Juggins, 1997).

Transfer function development

Modern foraminiferal distributions of Thornham Marsh

The study of the intertidal zone of Thornham Marsh has identified 33 dead foraminiferal species. The maximum number of species per sample is 23 and the mean sample foraminiferal abundance is 996 individuals/10 cm³.

The foraminiferal death assemblages are dominated by two agglutinated species, *Jadammina macrescens* and *Trochammina inflata*, and four calcareous species, *Ammonia beccarii*, *Elphidium williamsoni*, *Haynesina germanica* and *Quinqueloculina* spp. (Table 4). Unconstrained cluster analysis based on unweighted Euclidean distance (no transformation or standardization of the data) discriminates two cluster zones (Figure 2).

Table 3 Characteristics of study areas (cf. Figure 1)

Study area	Spring tidal range	Salinity	Site description
Alnmouth, Northumberland	macro (4.2 m)	10–30	On the banks of the Aln Estuary
Cowpen Marsh, Tees estuary	macro (4.6 m)	15–25	Within a small tidal creek connecting to the Tees estuary
Welwick Marsh, Humber estuary	macro (6.4 m)	5–35	North shore around the mid reach of the Humber estuary
Thornham Marsh, Norfolk	macro (6.0 m)	15–25	At the west end of the barrier system along the Norfolk coast
Brancaster Marsh, Norfolk	macro (6.0 m)	15–25	Behind the barrier system along the Norfolk coast
Bury Farm, Southampton Water	macro (4.0 m)	5–15	Upper reaches of the Southampton Water estuary
Keyhaven Marsh, Hampshire	macro (2.0 m)	10–30	Behind a shingle spit of the western Solent
Arne Peninsula, Poole Harbour	micro (1.2 m)	15–25	At the western margin of Poole Harbour in the lee of Round and Long Islands
Slimbridge, Severn Estuary	macro (12.2m)	5–30	Upper reaches of the Severn Estuary
Roudsea Marsh, Morecambe Bay	macro (8.4 m)	5–25	East shore adjacent to Roudsea Wood Nature Reserve at the top of the estuary
Nith Estuary, Solway Firth	macro (7.25 m)	5–25	East shore around the mid reach of the Nith estuary
Tramaig Bay, Jura	micro (1.6 m)	> 30	A small embayment with a narrow entrance and little freshwater input
Kentra Bay, Argyll	macro (4.4 m)	> 30	A sizeable embayment with a narrow entrance and little freshwater input

Table 4 The dominant foraminiferal taxa of the study areas

Study area	Tidal flat	Low marsh	High/middle marshes
Alnmouth, Northumberland	<i>Elphidium williamsoni</i> <i>Haynesina germanica</i>	<i>Miliammina fusca</i>	<i>Jadammina macrescens</i> <i>Trochammina inflata</i>
Cowpen Marsh, Tees estuary	<i>Elphidium williamsoni</i> <i>Haynesina germanica</i> <i>Quinqueloculina</i> spp.	<i>Miliammina fusca</i>	<i>Jadammina macrescens</i> <i>Trochammina inflata</i>
Welwick Marsh, Humber estuary	<i>Haynesina germanica</i>	Absent	<i>Jadammina macrescens</i>
Thornham Marsh, Norfolk	<i>Ammonia beccarii</i> <i>Elphidium williamsoni</i> <i>Haynesina germanica</i>	Absent	<i>Jadammina macrescens</i> <i>Trochammina inflata</i>
Brancaster Marsh, Norfolk	<i>Haynesina germanica</i>		<i>Jadammina macrescens</i> <i>Miliammina fusca</i>
Bury Farm, Southampton Water	<i>Ammonia beccarii</i> <i>Haynesina germanica</i>	Absent	<i>Haplophragmoides</i> spp. <i>Jadammina macrescens</i> <i>Miliammina fusca</i>
Keyhaven Marsh, Hampshire	<i>Ammonia beccarii</i> <i>Elphidium incertum</i>	<i>Miliammina fusca</i>	<i>Jadammina macrescens</i> <i>Trochammina inflata</i>
Arne Peninsula, Poole Harbour	<i>Ammonia beccarii</i> <i>Elphidium williamsoni</i> <i>Haynesina germanica</i>	Absent	<i>Haplophragmoides</i> spp. <i>Jadammina macrescens</i>
Slimbridge, Severn Estuary	<i>Ammonia beccarii</i> <i>Haynesina germanica</i>	Absent	<i>Trochammina inflata</i>
Roudsea Marsh, Morecambe Bay	<i>Haynesina germanica</i>	<i>Miliammina fusca</i> <i>Quinqueloculina</i> spp.	<i>Jadammina macrescens</i>
Nith Estuary, Solway Firth	<i>Haynesina germanica</i>	Absent	<i>Jadammina macrescens</i> <i>Miliammina fusca</i>
Tramaig Bay, Jura	<i>Elphidium magellanicum</i> <i>Elphidium williamsoni</i>	Absent	<i>Jadammina macrescens</i> <i>Trochammina inflata</i> <i>Miliammina fusca</i>
Kentra Bay, Argyll	<i>Elphidium williamsoni</i>	Absent	<i>Jadammina macrescens</i>

Zone T-I is dominated by *J. macrescens* with lower frequencies of *T. inflata* and *Q.* spp. and occurs within the high and middle marsh environment (defined by vascular plant distributions). It differs from other zones by having the highest percentages of *J. macrescens* (exceeds 28% of the total dead foraminifera in all samples) with a monospecific *J. macrescens* assemblage at the landward limit of the high marsh (station 1). Similar monospecific faunal assemblages have been well documented from marshes of northeastern North America

(Scott and Medioli, 1978; 1980; Gehrels, 1994). For example, along the upper edge of Chezzetcook Marsh, Nova Scotia, Scott and Medioli (1978; 1980) identified a 100% *J. macrescens* assemblage restricted to a 6 cm vertical range just below highest astronomical tide (HAT). They claimed that the upper boundary of this zone is indicative of HAT with an accuracy of ± 5 cm. However, cluster analysis did not identify this assemblage as a separate zone within Thornham Marsh; it was incorporated within zone T-I, which had an altitu-

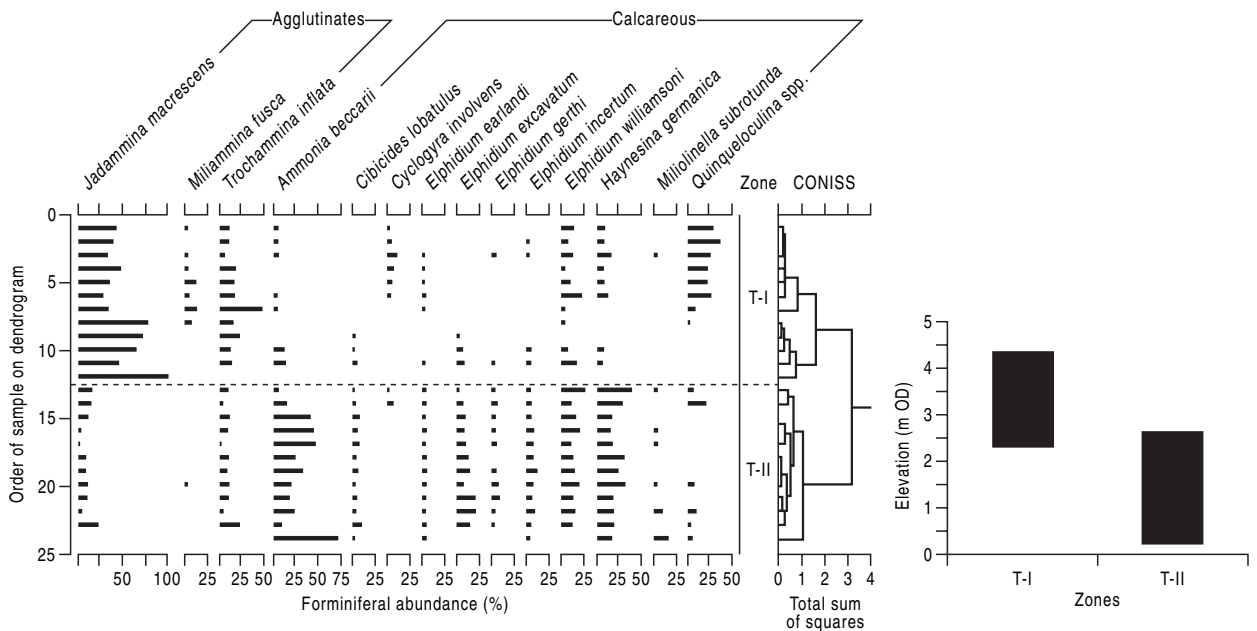


Figure 2 Unconstrained cluster analysis based on unweighted Euclidean distance of foraminiferal death assemblages from Thornham Marsh (only species greater than 10% are shown).

dinal range from 4.32 to 2.35 m OD (1.97 m). Monospecific *J. macrescens* zones are atypical of many other temperate and tropical intertidal environments because of modern disturbances at the rear of salt marshes due to human activities such as embankments, road and other structures (e.g., Brancaster Marsh). Zone T-II is dominated by calcareous species such as *A. beccarii*, *E. williamsoni* and *H. germanica*. The elevations range from 2.64 to 0.21 m OD (2.28 m).

Modern foraminiferal distributions of Brancaster Marsh

Thirty-one dead foraminiferal species have been identified in the intertidal zone of Brancaster Marsh. The maximum number of species counted is 19 and the mean sample foraminiferal concentration is 709 individuals/10 cm³.

The foraminiferal death assemblages are dominated by three agglutinated species, *J. macrescens*, *Miliammina fusca* and *T. inflata*, and three calcareous species, *E. williamsoni*, *H. germanica* and *Q.* spp. (Table 4). Cluster analysis of the assemblages detects two cluster zones (Figure 3). Zone B-I is dominated by three agglutinated species, *J. macrescens*, *M. fusca* and *T. inflata*. These three species account for at least 50% of the total dead foraminifera in all samples. The altitudinal range is from 3.27 to 2.98 m OD. Zone B-II is dominated by calcareous species such as *H. germanica* with lower frequencies of *J. macrescens*, *E. magellanicum* and *E. williamsoni*. It differs from the other zones by having the highest percentages of *H. germanica*, which exceed 30% of the total dead foraminifera in all samples. The elevations range from 2.48 to 1.85 m OD (0.63 m).

Environmental variables of Thornham and Brancaster Marshes

The porewater salinity of Thornham Marsh shows a general increase along the transect from a minimum of 6.9 at the landward limit of the high marsh to a maximum of 25.8 within the tidal flat. Similarly, pH increases along the transect from 5.3 to 7.0 at station 22. The grain-size distribution of the high and middle marsh are dominated by clay and silt size classes with the clay fraction decreasing from high to middle

marsh. However, the low marsh and tidal flat has a high sand content reaching a maximum of over 20% within the ridge and runnel sand bars. LOI decreases from 48.6% at the landward limit to 1.1% at seaward limit of the transect. The percentage vegetation cover shows a similar decline across the intertidal zone with a distinct threshold within the low marsh: vegetation cover decreases from 90 to 15%.

Porewater salinity, pH and grain size vary little across the intertidal zone of Brancaster Marsh. Salinity increases from a minimum of 7.2 at the landward limit of the marsh to a maximum of 13.8 within the low marsh. The minimum pH value (5.8) also occurs at the landward limit with the maximum (7.0) occurring within the tidal flat. The grain-size distribution of Brancaster Marsh is dominated by clay and silt size classes with higher sand fractions within the tidal flat. LOI and vegetation cover show a general decrease across the intertidal zone. LOI decreases from a maximum of 45.0% at the landward limit to a minimum of 11.9% at the seaward limit of the transect. The percentage vegetation cover shows a pronounced decrease between the low marsh and tidal flat from 90 to 0%.

The relationship between foraminifera and the environment

We used canonical correspondence analysis (CCA) of foraminiferal and environmental data from Thornham and Brancaster marshes to extract synthetic environmental gradients. These gradients were the basis for describing and illustrating the different habitat preferences (niches) of taxa via an ordination diagram. The independence and relative strength of the major environmental gradients were estimated using a series of partial CCAs to separate the total variation in the foraminiferal data into components which represent: (i) the unique contributions of individual environmental variables; (ii) the contribution of covariance between variables; and (iii) the unexplained variance. The statistical significance of the partial CCAs was determined using a Monte Carlo permutation test.

The sample-environment and species-environment biplots show that axis one (eigenvalue = 0.69) is correlated with SWLI, vegetation cover, LOI, pH and clay fraction, while axis two

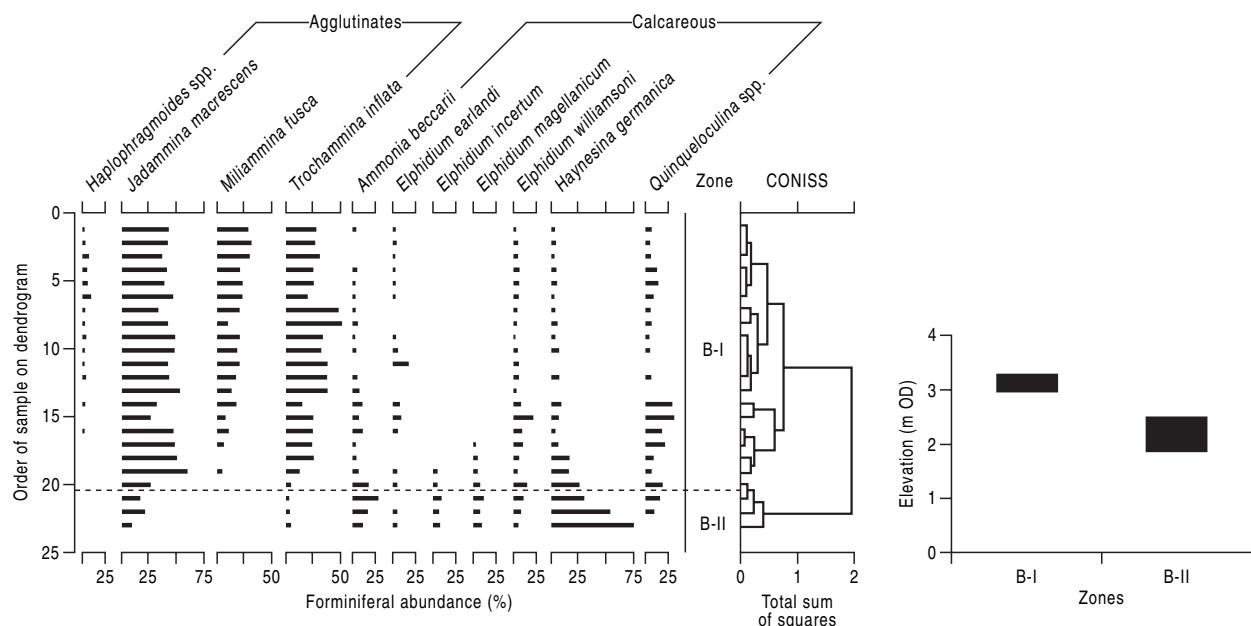


Figure 3 Unconstrained cluster analysis based on unweighted Euclidean distance of foraminiferal death assemblages from Brancaster Marsh (only species greater than 10% are shown).

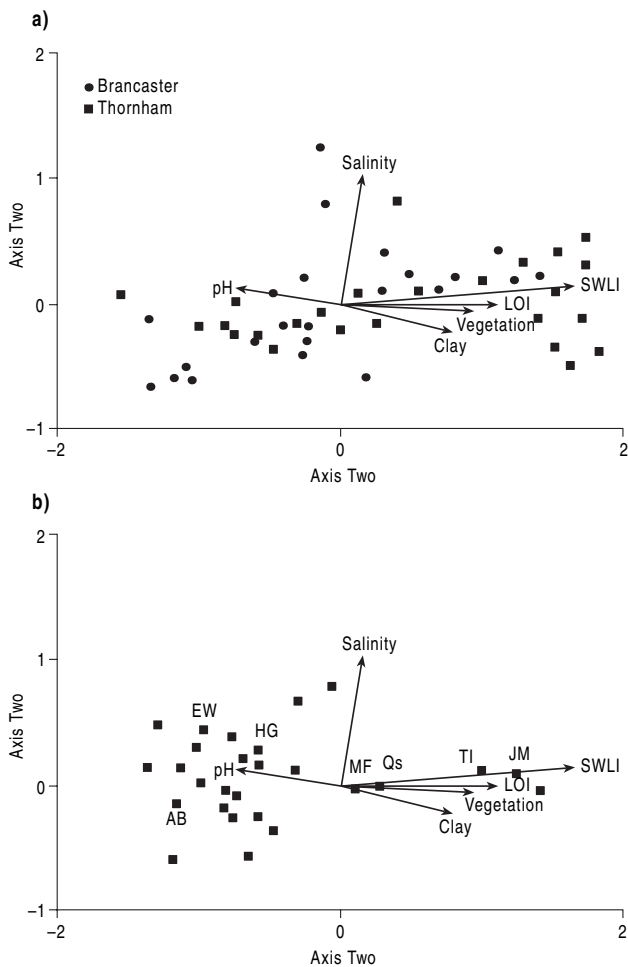


Figure 4 Canonical correspondence analysis biplots of (a) sample-environment and (b) foraminiferal species-environment. Site codes: circles = Thornham Marsh; squares = Brancaster Marsh. Species abbreviations: AB = *Ammonia beccarii*; EW = *Elphidium williamsoni*; HG = *Haynesina germanica*; JM = *Jadammina macrescens*; MF = *Miliammina fusca*; Qs = *Quinqueloculina* spp.; TI = *Trochammina inflata*. Environmental abbreviations: LOI = loss on ignition; SWLI = standardized water-level index.

(eigenvalue = 0.19) is correlated with salinity (Figure 4a). Therefore, axis one reflects the major gradient from high marsh plotted on the right (dense vegetation cover, high SWLI, LOI and clay fraction and low pH) to tidal flat plotted on the left (barren vegetation, low SWLI, LOI and clay fraction and high pH), while axis two reflects a salinity gradient. Partial CCAs show that the six environmental variables explain 52% of the total variance. This is composed of 23% (SWLI), 9% (salinity), 7% (LOI), 6% (vegetation cover), 5% (pH) and 5% (clay fraction), with the remainder consisting of intercorrelations between variables. The associated Monte Carlo permutation tests ($p = 0.01$, 99 random permutations) indicate that all environmental variables are highly significant and, therefore, each of these gradients accounts for a significant portion of the total variance in the foraminiferal data.

Species characteristic of a particular environment may also be identified on the species-environment biplot (Figure 4b). For example, *J. macrescens*, *M. fusca* and *T. inflata* occupy the ordination space on the right side of the diagram (high and middle marsh) and, conversely *A. beccarii*, *E. williamsoni* and *H. germanica* are found on the left side (tidal flat).

The CCA and partial CCA analyses, together with the vertical zonations of intertidal foraminiferal distributions of

Thornham and Brancaster marshes, suggest that the SWLI is the most important and statistically significant controlling variable.

Local and regional foraminifera-based transfer functions

A local transfer function was developed for SWLI based on 25 species and 47 samples from Thornham and Brancaster marshes (Table 5). These data were combined with data from 11 other intertidal zones from sites around the UK coast (Figure 1; Tables 3 and 4) to produce a regional data set consisting of 36 species and 160 samples. Figure 5 shows the relationship between observed and foraminifera-predicted SWLI, which illustrates the strong performance of the local ($RMSE_{\text{jack}} = 3.90$; $r_{\text{jack}}^2 = 0.89$) and regional ($RMSE_{\text{jack}} = 5.26$; $r_{\text{jack}}^2 = 0.79$) transfer functions.

Transfer function application

The local and regional transfer functions are applied separately to calibrate the fossil assemblages from core NNC17 and the resulting reconstructions compared. The calibration process assigns a SWLI to each fossil sample, and this is then back-transformed by rearranging equation (2) to express the former elevation of each sample in metres with respect to palaeo-mean tide level.

The fossil sequence of Holkham is characteristic of many UK coastal palaeoenvironments, and begins with a glacial diamict, overlain by a thin, well-humified basal peat, in this instance found at an elevation of -6.70 to -6.36 m OD. The peat is in turn overlain by an olive-grey silt-clay, containing dispersed organic remains and numerous bivalve fragments. Foraminiferal tests are absent in the diamict (Figure 6). Agglutinated species (e.g., *J. macrescens* and *T. inflata*) dominate the peat samples, indicating a salt marsh environment. In the overlying silt-clay, percentage frequencies of agglutinated species fall, reflecting the increased abundance of calcareous taxa. The assemblage is dominated by *A. beccarii*, *H. germanica* and *E.* species, and is indicative of estuarine or tidal flat environments. Towards the top of the core an increase in relative abundance of agglutinated taxa suggests a return to salt marsh conditions.

The reconstructed water levels reflect the changes in foraminiferal assemblages. The maximum water level ($FBTF_{\text{local}} = 3.11 \pm 0.25$ m, -6.34 m OD; $FBTF_{\text{regional}} = 3.42 \pm 0.34$ m, -6.32 m OD) occurs within the peat, associated with the agglutinated, salt marsh foraminifera, at the radiocarbon dated sedimentary horizon (7006–6494 cal. yr BP) and is indicative of deposition above MHWST. The water-level curve crosses a threshold at the transgressive contact and rapidly declines within the silt-clay to reach a minimum at -2.08 m OD ($FBTF_{\text{local}} = 0.65 \pm 0.25$ m; $FBTF_{\text{regional}} = 0.71 \pm 0.34$ m) between the IRSL and ^{14}C assays of 5100–4300 yr BP (-2.94 m OD) and 2672–2271 cal. yr BP (-1.61 m OD), respectively (Figure 7a and b).

Caution should, however, be exercised when applying such transfer functions since characteristics within the contemporary and fossil data may affect the accuracy of tide-level reconstructions. First, there is an uneven spatial sampling within the contemporary data with respect to SWLI. The majority of sites (70%) are found above approximately mean high water neap tide. Secondly, fossil assemblages can be altered by postdepositional changes of foraminiferal assemblages, particularly poor preservation of the calcareous tests within salt marsh deposits (Scott and Medioli, 1980), and

Table 5 Apparent errors of estimation and prediction errors from local and regional foraminifera-based transfer functions

Training set	RMSE		r^2		Maximum bias	
	Apparent	Prediction	Apparent	Prediction	Apparent	Prediction
Local	3.27	3.90	0.93	0.89	4.26	6.72
Regional	4.63	5.26	0.83	0.79	5.65	7.13

transport of tests from and into an assemblage (mixing). For example, Scott *et al.* (1980) have shown low marsh assemblages extending to shallow subtidal environments of eastern Canada. Unfortunately, there are no direct methods of detecting erroneous reconstructed reference water levels. Therefore, the most important indirect method is comparison with other lithostratigraphical, biostratigraphical and modelling techniques (see below).

Assessing the significance of spatial variability for transfer function development

The transfer function approach presented above is underpinned by foraminiferal surveys of modern taxa that seek to reliably quantify the relationships between individual species and sample elevation relative to the tidal frame. The precise and accurate quantification of these vertical relationships is fundamental to the reliability of the resulting transfer function and its reconstructions. Ideally, surface foraminiferal samples should be collected from a range of elevations and depositional environments analogous to those represented in the fossil material under investigation. One of the important decisions that must be made when compiling the modern training set is the spatial scale over which useful species-environment analogues may be found.

Two contrasting approaches have been employed in previous studies using microfossil data to reconstruct sea-level change. The first considers a local study to be most desirable, and concentrates on the collection of samples from a restricted geographical area (a single site or adjacent sites). The rationale behind this approach is that the conditions encountered on the modern marsh will be most applicable to those found in the fossil sediments recovered in core material. In this way, the influence of complicating factors, such as varying salinity and hydrographic regime, will be reduced. Gehrels (1994) highlights the problems associated with interand intrasite variability and recommends that transects be located as close to the core sites as possible to ensure errors are kept to a minimum. Allen and Haslett (2002) also prefer to use a local training set, arguing that including data from areas with different faunal characteristics, species ranges and oceanographic conditions is open to error.

The second approach is the antithesis of the first, and advocates the compilation of a modern training set from a range of sites with differing combinations of environmental variables (Horton *et al.*, 1999b). This methodology follows the premise that the best modern analogue for a past environment encountered in a sediment core may be found some distance from the study site. For example, in a study of Girdwood Flats in Alaska, Zong *et al.* (2003) found the best analogues for sediments associated with the 1964 earthquake and subsequent relative sea-level change in a site 150 km away, rather than within the local training set. The aim of a multisite approach is to gather a wide range of modern analogues that will permit the transfer function to perform reliably even if past environmental conditions at the study site differed significantly from those operating at the present day. In this paper, we assess these contrasting approaches by comparing the relative performance of the local and regional transfer functions when applied to the Holkham core NNC17.

Figure 7 reveals that both transfer functions reproduce a broadly similar pattern of elevation change and demonstrates that the general trends are reproducible and independent of the precise method used. The performance statistics for both transfer functions show that the $FBTF_{local}$ reconstruction

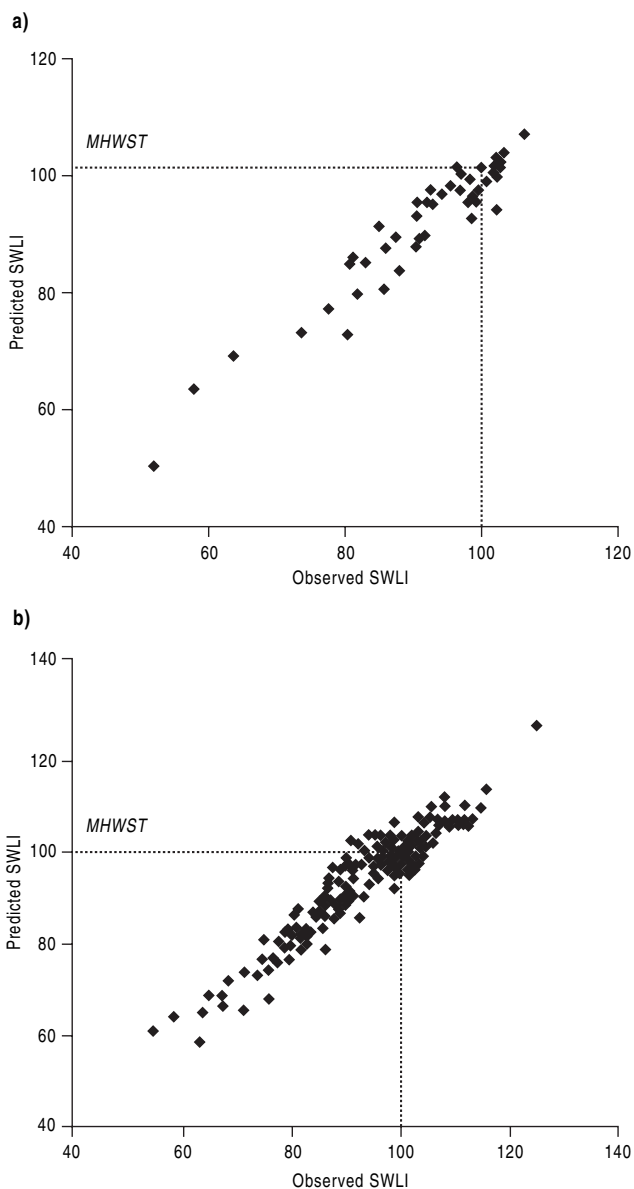


Figure 5 Scatter plots showing the relationship of the observed standardized water-level index (SWLI) versus foraminifera-predicted SWLI using (a) local and (b) regional weighted average partial least squares transfer function.

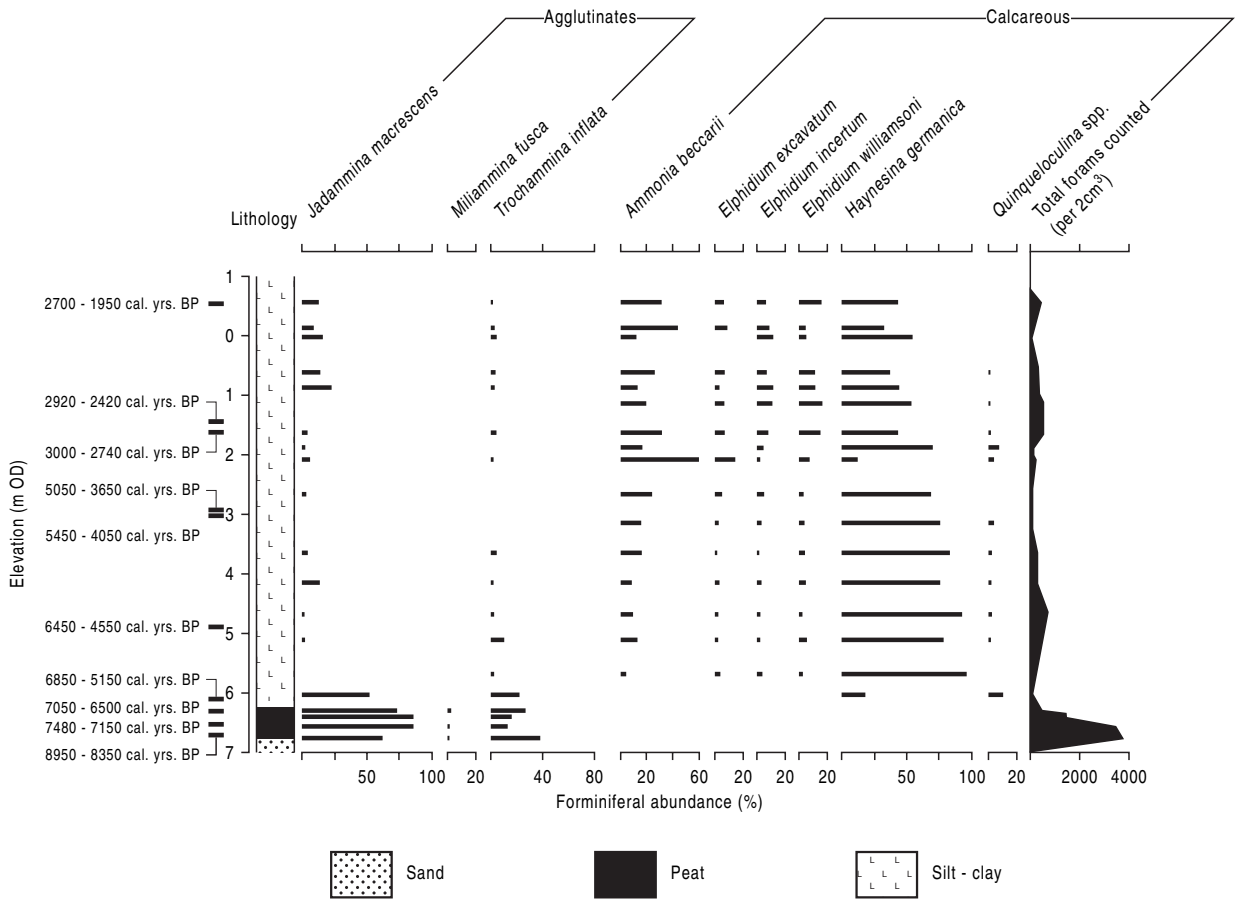


Figure 6 Holkham core NNC 17 foraminiferal diagram. Foraminiferal abundance is calculated as a percentage of total foraminiferal tests (only species greater than 10% are shown). Calibrated radiocarbon and IRSL ages, and elevation (m OD) are shown to the left of the lithology column. The sediment legend is drawn according to Troels-Smith (1955).

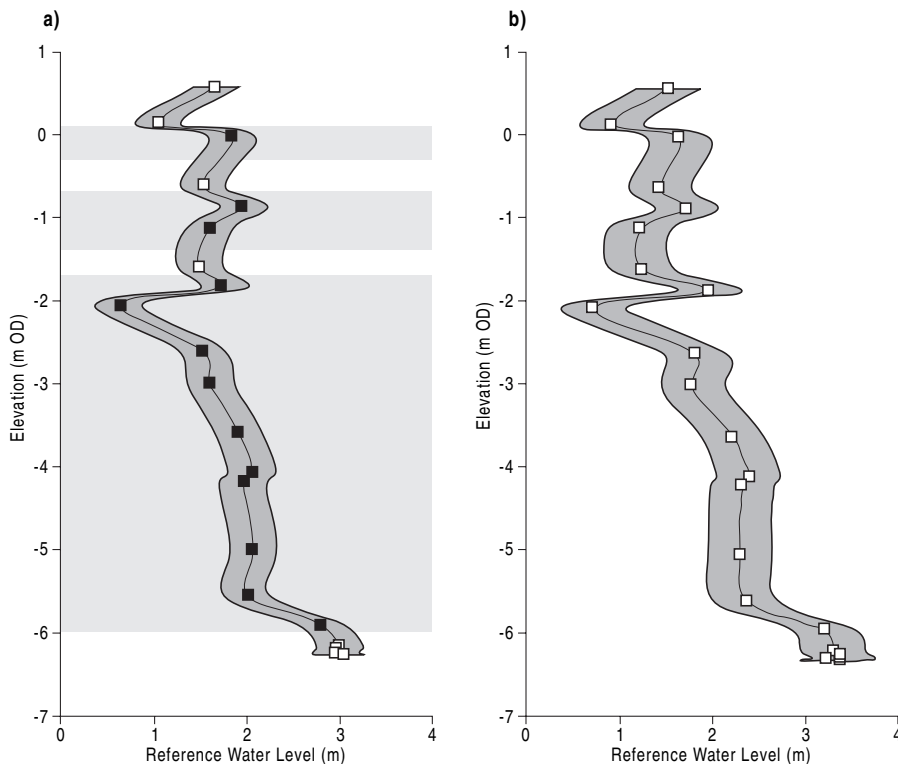


Figure 7 Reference water-level reconstructions for Holkham core NNC 17 using (a) local and (b) regional foraminifera-based transfer functions. Filled squares indicate sample with no modern analogue.

have error terms 0.09 m smaller than those of the $FBTF_{\text{regional}}$ (Table 6). The greater precision of the $FBTF_{\text{local}}$ is to be expected given that the regional training set is derived from 13 sites with a great variety of tidal, sedimentological and floral characteristics. However, the magnitude of this difference is small when compared with the overall magnitude of the error terms associated with each FBTF and the potential errors inherent in marsh sea-level reconstructions (e.g., tidal range change, sediment consolidation). Consequently, the increased precision of the $FBTF_{\text{local}}$ does not represent a significant improvement in performance.

Of potentially greater significance is the fact that reconstructed elevations produced by the local transfer function differ from their regional counterparts by as much as 0.43 m (Table 5). The reason for these large discrepancies is apparent when the presence of samples associated with ‘no modern analogue’ conditions (shown as black squares in Figure 7) are considered. Of the 23 reconstructed elevations produced by the local transfer function, 14 are without modern analogues and must therefore be treated with caution. In contrast, all fossil samples have modern analogues in the regional training set, and these reconstructions are therefore considered to be reliable. Consequently, the reconstructions generated by the $FBTF_{\text{regional}}$ represent a significant improvement in reliability compared to those associated with the $FBTF_{\text{local}}$.

It is instructive to consider the occurrence of ‘no modern analogue’ samples associated with the local training set. The ‘no modern analogue’ situations arise when the reconstructed tide levels indicate deposition in low marsh to tidal flat environments and the percentage of *A. beccarii* or *H. germanica* are greater than 58% and 44%, respectively. These situations could be generated by limitations in the local training set, which contains 9% fewer samples from low intertidal environments than the regional training set. So, while a comparable range of elevations is present in both the local and regional training sets, the local data set only has four samples with equivalent percentages of *A. beccarii* or

H. germanica compared to 29 for the regional counterpart, reflecting the inevitably larger sample size and species diversity of the latter (160 samples in comparison with 47 samples; 36 species compared with 25 species).

Alternative explanations for an absence of modern analogues include the presence of infaunal foraminifera or post-depositional modification of fossil assemblages by transport, erosion or dissolution (Murray and Alve, 1999). We do not consider these factors to be capable of producing the observed patterns of ‘no modern analogues’. Living infaunal foraminifera (e.g., Goldstein and Harben, 1993) do not appear to be significant in the predominantly minerogenic marshes of the UK, where anoxic conditions are often encountered just below the marsh surface (Horton, 1999). If transport, erosion or dissolution were responsible, it would be necessary to invoke a mechanism to explain why it should influence the local training set so much more than the regional one. The fossil foraminiferal assemblages from Holkham show no signs of abrasion or etching, and do not possess significant proportions of shelf species. Most of the no modern analogue situations are triggered by high relative abundances of *A. beccarii* or *H. germanica*, and mechanisms of selective calcareous test destruction or transport would need to be invoked.

A more cogent explanation is that local conditions are not representative of the full suite of environments encountered in the core sediments. This accounts for the differences between the transfer functions and also explains why most reconstructions derived from salt marsh sediments have local analogues while many of those from the tidal flat samples do not. Foraminiferal assemblages recovered in the highest marsh environments are relatively homogenous, irrespective of local conditions such as salinity and tidal range, but the composition of the lower marsh to tidal flat assemblages is more strongly controlled by conditions in the adjacent estuary/sub-tidal environment (Scott and Medioli, 1980). An absence of modern analogues in the local training set would be produced if environmental parameters at the site, such as salinity, hydro-

Table 6 A summary of the reference water level (RWL) and indicative range predictions generated by the local and regional foraminifera-based transfer function (FBTF) for samples from the Holkham core NNC17. The critical value (10th percentile) for the dissimilarity coefficients (Min. DC) produced by the modern analogue technique for the $FBTF_{\text{local}}$ is 0.12 and $FBTF_{\text{regional}}$ is 0.24

Sample elevation (m OD)	Local		Regional			
	RWL	Min. DC	Analogue	RWL	Min. DC	Analogue
0.57	1.72±0.25	0.09	Good	1.54±0.34	0.10	Good
0.12	1.08±0.25	0.12	Good	0.91±0.34	0.15	Good
-0.03	1.89±0.25	0.20	No close	1.64±0.34	0.21	Good
-0.63	1.58±0.25	0.08	Good	1.43±0.34	0.08	Good
-0.88	2.03±0.25	0.19	No close	1.73±0.34	0.20	Good
-1.13	1.65±0.25	0.29	No close	1.22±0.34	0.24	Good
-1.63	1.53±0.25	0.11	Good	1.24±0.34	0.11	Good
-1.88	1.80±0.25	0.20	No close	1.97±0.34	0.12	Good
-2.08	0.65±0.25	0.17	No close	0.71±0.34	0.17	Good
-2.63	1.57±0.25	0.24	No close	1.81±0.34	0.09	Good
-3.03	1.66±0.25	0.21	No close	1.79±0.34	0.12	Good
-3.63	1.96±0.25	0.15	No close	2.21±0.34	0.07	Good
-4.13	2.11±0.25	0.14	No close	2.40±0.34	0.10	Good
-4.23	2.02±0.25	0.16	No close	2.32±0.34	0.05	Good
-5.06	2.12±0.25	0.20	No close	2.30±0.34	0.12	Good
-5.63	2.07±0.25	0.20	No close	2.37±0.34	0.05	Good
-5.98	2.89±0.25	0.14	No close	3.22±0.34	0.15	Good
-6.24	3.08±0.25	0.05	Good	3.32±0.34	0.05	Good
-6.28	3.04±0.25	0.06	Good	3.40±0.34	0.06	Good
-6.30	3.04±0.25	0.06	Good	3.40±0.34	0.05	Good
-6.32	3.03±0.25	0.06	Good	3.42±0.34	0.04	Good
-6.34	3.11±0.25	0.08	Good	3.23±0.34	0.06	Good

graphic or sedimentological conditions, had altered through time. Lithological analysis supports this interpretation, since the modern tidal flat samples have a relatively coarse grain size that is quite distinct from the fine-grained sediments recovered in the core.

Holocene sea-level change

In order to further examine the reliability of the transfer function approach, the reconstructions derived from the FBTF_{regional} are compared with existing geophysical modelling (ICE 4G model; Peltier *et al.*, 2002) and sea-level data from the study area (Shennan and Horton, 2002) (Figure 8). The shaded curve of mean sea-level change is extracted from the transfer function output by combining the reconstructions with the elevation of each sediment sample. These variations are then placed in a temporal framework using the age-depth relationships established from the chronological data (Table 2). The reconstructed elevations derived from the transfer function may be influenced by sediment consolidation in the same way as the sea-level index points.

Figure 8 illustrates that the general pattern of mean sea-level change indicated by the FBTF is consistent with existing geologically based sea-level data, and the results of geophysical modelling studies. In common with other ice-marginal regions, the general pattern of RSL change is of an initially rapid rise during the early Holocene, followed by a mid-Holocene slowdown. In north Norfolk, the long-term trend for the late Holocene has been estimated at -0.76 mm/yr (Shennan and Horton, 2002). The foraminifera-based curve exhibits greater variation than the ICE4G glacial isostatic adjustment model predictions (Peltier *et al.*, 2002) but this is to be expected given the latter's inability to capture such shorter period (submillennial) variability. Furthermore, the FBTF sea-level curve runs

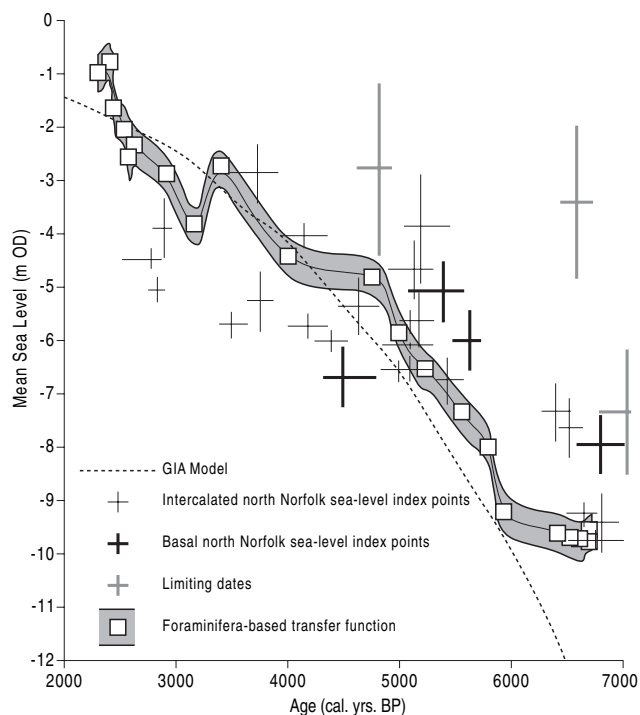


Figure 8 Reconstruction of Holocene mean sea-level curve for Holkham core NNC 17 using the foraminifera-based transfer function (regional). Glacial isostatic adjustment (GIA) model ICE4G (Peltier *et al.*, 2002) and sea-level index points from north Norfolk (see Shennan and Horton, 2002) are shown.

through the centre of the scattered sea-level index points. Of the 26 sea-level index points from north Norfolk, 11 plot on the FBTF sea-level curve, while eight plot above and seven plot below. The scatter apparent in the sea-level index points is typical of most age-elevation data from around the UK and illustrates the difficulties associated with resolving submillennial-scale variability. The scatter includes the total influence of local-scale processes and also any differential isostatic movements. Local-scale processes operating within the north Norfolk area may include variable sedimentation rates, changes in hydrographic characteristics and postdepositional sediment consolidation (Shennan and Horton, 2002). The effects of consolidation can be especially severe for index points and transfer function reconstructions from samples which are found above or below considerable thicknesses of Holocene sediment. In contrast with other sea-level data, however, the sequential nature of the transfer function data means that the resulting patterns are readily testable by the collection of data from supplementary boreholes. As additional data are collected, the patterns of change may be refined and, where discrepancies arise, may provide valuable information on complicating factors such as tidal-range change or compaction which have proven so hard to quantify and remain a significant stumbling block in the pursuit of reliable RSL reconstruction.

Conclusion

Foraminiferal transfer functions are ideally suited to the generation of high-resolution records of RSL change because they expand the range of sediments that can be used in sea-level reconstruction. The reliability of this approach rests firmly upon the precise and accurate determination of the modern relationships between foraminiferal distributions and elevation relative to the tidal frame. These relationships depend, in turn, upon the selection of appropriate modern analogues for the types of sedimentary environments that will be represented in core material.

The results presented in this paper suggest that transfer functions developed from regional training sets are better suited to the analysis of fossil material than those derived from local data since they incorporate a greater range and variety of modern analogues. Local training sets, while giving a slight increase in precision, suffer from severely restricted predictive power due to the abundance of 'no modern analogue' situations. We suggest that interpretations based on transfer functions derived from local training sets should be treated with caution unless the constancy of environmental conditions at the sample site can be demonstrated (e.g., via a matching analogue technique). Intuitively, these conditions will be most satisfactorily met when dealing with 'young' high points and modelling data. This demonstrates that the FBTF approach can provide a useful first assessment of sea-level change within a study area. The reliability of FBTF reconstructing will be strengthened, and the pattern of change refined, by the development of higher-resolution accumulation histories and the analysis of replicate cores. The collection of this type of sequential data has the potential to produce the sort of high-resolution records of sea-level change that are necessary to further research into submillennial sea-level variability.

A data repository of all foraminiferal and environmental data can be found on the following website: <http://www.sas.upenn.edu/earth/people>.

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