1   **Reconstruction of recent sea-level change using testate amoebae**

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Abstract

Proxy-based sea-level reconstructions place the instrumentally observed rates of recent sea-level rise in a longer term context by providing data that extend the instrumental sea-level record into past centuries. This paper presents the first sea-level reconstructions based on analyses of testate amoebae, to test their capability to improve the precision of past sea-level reconstructions. We used sample preparation methods commonly used in peatland studies, but applied a modified sample preparation based on a weak alkali treatment to improve the efficiency of the counting process. We present two reconstructions for the past 100 years from sites in Maine (USA) and Nova Scotia (Canada) based on short cores from salt marshes and modern training data from North America and the United Kingdom. These are compared with tide-gauge records and reconstructions based on foraminifera from the same cores. The reconstruction from the Chezzetcook marsh (Nova Scotia) shows good agreement with both the tide-gauge and the foraminifera-based reconstruction and is insensitive to the modern training set and underlying transfer function model. The Wells (Maine) reconstruction is also consistent with the tide-gauge record and foraminifera-based reconstruction, but shows greater variability depending on methodology applied. The precision of testate amoebae-based reconstructions is higher than those for foraminifera, but further work on surface samples is needed to improve the accuracy of reconstructed values. The UK data perform well in predicting known elevations of North American surface samples, and sea-level reconstructions based on the UK transfer function are very similar to those based on the North American data, suggesting the methodology is robust across large geographical areas. We conclude that testate amoebae have the potential to provide robust, higher precision sea-level reconstructions for the past few centuries if modern transfer functions are improved and core sites are located within the main zone of testate amoebae occurrence on the saltmarsh.

1. Introduction

Sea-level change is one of the most important aspects of future global change and understanding the causes, rates and geographical and temporal variability of sea level is crucial to improving predictions of 21st century sea-level rise. Measurements and reconstructions of past sea level play an important part in improving understanding of sea-level change (Bindoff et al., 2007). Tide-gauge records and satellite data provide high temporal resolution data, but the temporal and spatial coverage of these records is limited. Reconstructions of sea-level change over the past few millennia are therefore critical to understanding the dynamics of sea-level change and there are a growing number of reconstructions for locations around the world (e.g. Varekamp et al., 1992; van de Plassche et al., 1998; Donnelly et al., 2004; Gehrels et al., 2002; 2005; 2008). Recent research has used high temporal resolution records to show that current rates of sea-level rise are two to three times faster than longer terms rates over previous centuries (Gehrels et al., 2005). Whilst this longer term context for individual locations is important, it does not necessarily help test hypotheses concerning the causes and sources of the recent acceleration in sea-level rise, unless an appropriate spatial and temporal network of reconstructions exists. Adequate spatial and temporal coverage of sea-level change over the last few hundred years can only be provided by palaeoenvironmental records, due to the spatial bias in tide gauge records to the northern hemisphere.

The most detailed and precise late Holocene sea-level reconstructions are based on the use of salt-marsh foraminifera as sea-level indicators. Statistical analyses indicate that in most locations the precision of sea-level positions reconstructed from foraminifera is on the order of ±20 cm (Gehrels, 2000; Edwards and Horton, 2000; Horton et al., 1999a; 1999b) while only along microtidal coastlines, such as the Atlantic coast of Nova Scotia, Canada, the precision is better than ±10 cm (Gehrels et al., 2005). In most mid-latitude North Atlantic locations the rise of sea level in the past century has been around 10-20 cm (Holgate, 2007; Woodworth et al., 2008). If an attempt is made to detect the onset of this recent rapid rise it is therefore desirable to use sea-level indicators that have higher precision than those offered

68   by foraminifera. Diatoms improve precision in some contexts but testate amoebae appear to

69   have particular potential as high-precision indicators in saltmarsh sediments with tightly

70   constrained zonation in relation to elevation in the upper marsh and supra-tidal zones

71   (Charman et al., 1998; Gehrels et al, 2001; Charman et al., 2002). However, apart from an

72   initial assessment of samples from a range of sedimentary contexts (Roe et al., 2002) there

73   have been no attempts to use testate amoebae to develop and test high resolution records of

74   sea-level change.

75   This paper reports the results of testate amoebae analysis on two saltmarsh cores

76   from the Atlantic coast of North America to demonstrate the use of testate amoebae as high-

77   precision sea-level indicators capable of detecting fluctuations of the order of ±10 cm over

78   multi-decadal to centennial timescales. Our reconstructions are assessed against nearby

79   tide-gauge data and published sea-level reconstructions based on foraminifera. We also

80   suggest an improved preparation procedure that overcomes some of the difficulties

81   associated with counting low concentrations of testate amoebae in organic silty sediments

82   that are typical of high marsh settings (Roe et al., 2002).

83

84   **Testate amoebae as sea-level indicators**

85   Testate amoebae (or 'thecamoebians') are a group of test-forming protozoa some of which

86   are related to foraminifera. They are known to be good indicators of hydrological conditions

87   in peatlands (*e.g.*, Tolonen, 1986; Charman et al., 2006). Testate amoebae have also been

88   reported in salt-marsh environments (*e.g.*, Scott et al., 1991; 1995a) in samples prepared for

89   foraminiferal analyses, but only in low numbers and low diversity in the size fraction 63-500

90   μm. We have collected testate amoebae from surface sediments in salt marshes in the UK

91   (Charman et al., 1998; 2000a; 2002; Gehrels et al., 2001; Roe et al., 2002) and along the

92   eastern seaboard of North America (Gehrels et al., 2006). In these investigations we have

93   applied techniques commonly used in peatland studies (Hendon and Charman, 1997) and

94   examined the fraction between 15 and 63 μm in addition to the 63-500 μm fraction. Our

95   results indicate that small testate amoebae (<63 μm) are much more abundant and diverse

96   in salt-marsh sediments than the larger testate amoebae (>63 μm). The vertical distribution

97   of testate amoebae is distinctly zoned on the surface of salt marshes, and shows a stronger

98   zonation than that of diatoms and foraminifera in the highest levels of marshes (Gehrels et

99   al., 2001). Testate amoebae can be found as low as the level of mean high spring tide but

100 their vertical extent reaches upward into areas well above the highest limit of foraminifera.

101 Based on quantitative analyses of modern datasets we have concluded that testate amoebae

102 may be capable of resolving sea-level positions with a precision perhaps as low as ±4 cm in

103 microtidal sites, provided that fossil testate amoebae are present and well preserved in

104 subsurface sediments (Gehrels et al., 2006). This study represents the first systematic

105 attempt to use fossil testate amoebae to reconstruct recent sea-level change.

106

107 **Site descriptions and previous work**

108 We sampled cores from two previously studied sites in Maine and Nova Scotia (Figure 1).

109 The Webhannet marsh in Wells, Maine (43°18'N, 70°34'W) is a backbarrier marsh along the

110 Wells embayment in southwestern Maine (USA). The marsh is connected to the Gulf of

111 Maine by a flood-dominated tidal inlet and the mean tidal range in the marsh is 2.64 m

112 (Gehrels, 1994). The sea-level history has previously been determined from salt-marsh plant

113 fossils (Belknap et al., 1989) and foraminifera (Kelley et al.,1995; Gehrels et al., 1996; 2002).

114 The core selected for the present study is core FS-1 from the high marsh zone where

115 *Spartina patens* is the dominant plant cover. This core was first analysed for foraminifera by

116 Gehrels et al. (2002) and formed the basis for a detailed sea-level chronology spanning the

117 past 1200 years. The sea-level curve for Wells compared well with a curve produced for

118 Machiasport in eastern Maine and is therefore interpreted to be representative for the Gulf of

119 Maine. In the past 100-200 years the Gulf of Maine has experienced 0.3-0.4 m of relative

120 sea-level rise, the fastest rise in the past millennium. Gehrels et al. (2002) suggested that

121 sea-level rise may have been slow in the middle of the 19th century, but the precision of their

122 reconstruction precluded a clear distinction between pre- and post-industrial rates of sea-

123 level rise.

124   The Chezzetcook Inlet is located 45 km ENE of Halifax, Nova Scotia (Canada) and is

125   micro- to mesotidal with a tidal range of 2.14 m at the mouth of the inlet. Tidal range is

126   reduced to 1.86 m at the West Head location where core CZ-25 is located in the high marsh

127   zone dominated by *Spartina patens* (Gehrels et al., 2005). Chezzetcook Inlet has been the

128   site of previous Holocene sea-level studies, including those by Scott (1977), Scott et al.

129   (1987; 1995b) and Gehrels et al. (2004; 2005). Gehrels et al. (2005) established a high-

130   resolution sea-level reconstruction for the last 1000 years based on foraminifera and showed

131   a doubling of the rate of sea-level rise, from 1.6 mm yr^{-1} to 3.2 mm yr^{-1}, shortly after c. AD

132   1900.

133

134   ***Laboratory methods***

135   Standard preparations for testate amoebae samples are water-based sieving to separate the

136   15-300 μm fraction for counting at 100-1000x magnification under a light microscope

137   (Charman et al., 2000b). However, in fossil and some surface samples, this process retains a

138   large amount of silt-sized organic remains that can obscure the tests, rendering samples

139   difficult or impossible to count to totals that are appropriate for statistical analysis. Previous

140   assessments on terrestrial peat have shown that typical pollen preparation processes and

141   other chemical treatments damage or destroy tests and so are not generally used. However,

142   low strength alkali treatment prior to sieving can remove organic aggregates. Although there

143   is some alteration of structure, tests are not destroyed and can still be identified (Hendon and

144   Charman, 1997). We used a modified procedure of Hendon and Charman (1997), including

145   pre-treatment with 5% KOH to eliminate unwanted detritus. We compared counts from eight

146   test samples from the Wells core, with and without KOH treatment to assess the effects on

147   test numbers and concentrations. Following this preliminary test, we applied the same

148   preparation process to all fossil samples.

149   Samples of 0.2-0.5 ml from 1cm thick slices were collected from the cores and

150   weighed. One tablet of *Lycopodium clavatum* L. was added as an exotic marker (Stockmarr,

151   1971). Samples were boiled in 100 ml distilled water for 5-10 minutes, stirred occasionally to

152   aid disaggregation and left soaking overnight. The next day, samples were sieved and the

153   fraction of 15-300 μm was retained for analysis. A 4 ml solution of 5% KOH was added and

154   samples were warmed at approximately 80°C for 1-2 minutes and sieved again at 15 μm to

155   remove more fine detritus. Finally, samples were mounted in glycerol or water onto a

156   microscope slide with a 22x40 mm cover slip sealed with nail varnish. In the initial test of

157   KOH treatment, testate amoebae were counted until 150 *Lycopodium* spores had been

158   counted. In the full counts of fossil samples, at least 50 tests were counted. The time-

159   consuming nature of the counting procedure precluded the counting of more specimens, but

160   the number of 50 individuals is sufficient in the absence of rare taxa (those that occur in very

161   low abundances of perhaps <5%; Patterson and Fishbein, 1991). Data from some samples

162   with <50 specimens are also included in the results section but these data are not used for

163   transfer functions or sea-level reconstructions.

164   A series of transfer functions based on surface samples of testate amoebae were

165   applied to the fossil data using the program C2 (Juggins, 2003). Two main data sets were

166   used for this. First, we tested several different transfer functions based on data from two

167   marshes in the region, consisting of 29 surface samples from the Little River Marsh

168   (approximately 4 km from the Wells core site) and the Little Dipper Harbour marsh in New

169   Brunswick (Gehrels et al., 2006). These data sets are illustrated in Figure 2 as taxon

170   abundance plotted against surface elevation and show the strong zonation of taxa along the

171   tidal gradient. We also applied a local transfer function to the Wells data based only on the

172   17 samples from the Little River Marsh, although this has the disadvantage that sample

173   numbers are too low to generate sample specific error estimates. Second, we tested a

174   similar series of transfer functions based on modern data from the United Kingdom

175   (Charman et al., 2002) to test whether taxon-environment relationships are robust across the

176   North Atlantic region. If modern relationships are spatially robust, it is more likely that the

177   transfer functions are also temporally robust. To assess this, the best performing transfer

178   function in cross validation of the UK data was applied to the modern North American

179   samples as well as to the fossil samples. In order to combine data from sites with different

180   tidal ranges, elevation data were normalised in relation to the difference between mean tidal

181   level (MTL) and highest astronomical tide (HAT).

182   The chronologies for the cores were based on radiocarbon, ^{210}Pb,^{137}Cs, ^{207}Pb/^{206}Pb ratios

183   and pollen analyses (Gehrels et al., 2002; 2005). For Chezzetcook, the age-depth model is

184   based on ^{210}Pb ages for the upper part of the profile, cross-checked against ^{207}Pb:^{206}Pb ratios

185   and ^{137}Cs, and extrapolated for ages prior to c. AD 1890 to a pollen marker at AD 1780 ± 20

186   years (Gehrels et al., 2005, Figure 8b). For Wells, the chronology is based on ^{210}Pb cross

187   checked against ^{137}Cs and extrapolated to a pollen marker at AD 1760 (Gehrels et al', 2002,

188   Figure 2). The samples used for testate amoebae analysis date almost entirely from the

189   sections of the cores dated by ^{210}Pb to post AD 1900, supported by ^{137}Cs and ^{207}Pb:^{206}Pb

190   ratios. For the Wells core, we also tested for the presence of spheroidal carbonaceous

191   particles (SCPs), markers for industrial pollution found widely in lake and peat sediments but

192   not reported from saltmarsh deposits (Rose, 2001).

193

194   **3. Results**

195   ***Effect of KOH treatment***

196   A total of 60 tests were counted in the eight samples prepared by standard water-based

197   techniques (Table 1). Both the count (29) and the concentration (56.4 mg^{-1}) were highest in

198   the sample from 8-9 cm depth, with other samples having counts between 1 and 8 tests,

199   representing concentrations of 4.9-18.1 tests mg^{-1}. Counts were higher overall in the samples

200   treated with KOH (71 tests counted) and concentrations were also increased in the samples

201   from 32 cm and above where counts were highest. Deeper samples had very low counts

202   (<10) and concentrations (<10 mg^{-1}) in both treatments and generally showed reduced

203   counts and concentrations following KOH treatment. The assemblage composition of the

204   samples with counts >10 is very similar between treatments with most of the same dominant

205   taxa present. Furthermore, although we did not quantify counting effort, the slides were

206   generally clearer with better dispersal of material and reduced amounts of fine organic

207   material visible. We conclude that the weak 5% KOH treatment improves overall quality of

208   slides without selective effects on the assemblage. Increased concentrations in the KOH

209   treatment suggest that tests are hidden by detritus in the water-based treatment. Although

210   the numbers and range of samples and tests counted was not adequate to be conclusive, the

211   results also indicate that damage to tests was not significant enough to prevent detection and

212   identification of all taxa. Hendon and Charman (1997) also reported increased concentrations

213   of tests following a stronger 10% KOH treatment, but found significant damage to tests. Our

214   results suggest a lower concentration of KOH retains the benefit of reduced detritus while

215   avoiding problems of test damage. This is an area still requiring further work and a

216   systematic experiment to determine optimum combinations of KOH concentration,

217   temperature and length of treatment.I It seems likely that weak alkali treatments of

218   problematic samples with low test concentrations improves counting efficiency and increases

219   the numbers of samples from which data can be obtained, but we would not advocate using

220   this process in the absence of some evaluation of its impact on specific samples and

221   assemblages.

222

223   **Modern assemblages and transfer functions**

224   *North American data*

225   The modern assemblages (Figure 2) show a strong zonation from elevations below mean

226   higher high water (MHHW) extending to well above highest astronomical tide (HAT) and

227   zonation is similar for both sites. A full discussion of the modern assemblages is given by

228   Gehrels et al. (2006), but we include these data here to allow comparison with the fossil

229   assemblages. The highest occurrence of foraminifera is at (Little River) or just below (Ltitle

230   Dipper) HAT, where dominant testate amoebae are *Centropyxis cassis* type, *Euglypha*

231   *rotunda* type and *Tracheleuglypha dentata.* . The lowewrmost samples are dominated by

232   taxa such as *Digglugia pristis* type *and Centropyxis platystoma* type

233

234 Transfer functions based on weighted averaging performed best in leave-one-out cross

235 validation (Table 2), with no improvement from using a partial-least-squares version of

236 weighted averaging. A linear-based partial-least-squares model performed similarly and two

237 approaches based on modern analogue matching were significantly worse. The weighted

238 average model based on classic deshrinking (WA_Cla) had the highest r^2 (0.85), lowest

239 maximum bias and low RMSEP and was applied to the fossil data sets. For comparison with

240 a tolerance downweighted model, which is potentially more stable in reconstructions, the

241 WAT_Cla model was also applied.

242

243 *UK data*

244 The UK data set consists of modern samples from three sites (Taf estuary, S.Wales; Erme

245 estuary, Devon; Brancaster marsh, Norfolk). Previously these data were used to examine a

246 variety of relationships between testate amoebae and environmental conditions (Charman et

247 al., 2002) and to test the potential of multi-proxy microfossil data for sea-level reconstructions

248 (Gehrels et al., 2001). Here we test the ability of these data to estimate the known elevation

249 of the modern samples from the North American marshes in order assess the applicability of

250 transfer functions over very wide geographical regions..

251

252 The transfer functions for the UK data suggest very good performance of some models

253 (Table 3). In particular, the linear partial least squares (PLS) model produced very high r^2

254 (0.99) and low RMSEP (0.012) values. The modern analogue technique also produced good

255 cross validation statistics (r^2=0.61, RMSEP=0.063), but the residuals were systematically

256 biased with strong over-prediction in low elevation samples and under-prediction in high

257 elevation samples (plot not shown). The best performing weighted average model (WAT_Inv;

258 tolerance downweighted weighted average with inverse deshrinking) had a good r^2 (0.47)

259 and low RMSEP (0.074). Both the PLS and WAT_Inv models were applied to the US

260 samples to assess their applicability to North American data (Table 3, Figure 3).

261 Performance in terms of RMSEP (Table 3) was surprisingly good for both transfer functions,

262   although both tended to show a systematic bias towards over prediction at low elevations

263   and under-predictions at higher elevations (Figure 3a). This tendency was much more

264   extreme for the PLS model.

265

266   Normalising the data to the height between MTL and HAT is necessary in order to take

267   account of differing tidal range between sites for transfer-function development based on

268   more than one site, but for reconstruction of past sea level, these values are converted back

269   to actual elevation using the modern tidal range for the site concerned. It is assumed that

270   tidal range remained unchanged, which is reasonable for reconstructions covering only the

271   last 100 years. We therefore tested the ability of different transfer functions to estimate the

272   actual elevation for the modern samples at the US sites, as an improved test of model

273   performance (Figure 3b). The tendency of the PLS model to underestimate the difference in

274   elevation between samples was even more marked here, whereas the WAT_Inv model either

275   slightly under-estimated (Little River) or slightly over-estimated (Little Dipper) this difference.

276   Although the PLS model shows consistently higher statistical performance in cross validation

277   (Table 3) than the WAT_Inv model, the WAT_Inv model is therefore a much more robust

278   model for reconstructions. In particular, the characteristics of the WAT_Inv model mean that

279   it is much more likely to give accurate estimates of multi-decadal *trends* in reconstructions

280   from fossil samples, a key aim in high temporal resolution studies (e.g. Gehrels et al., 2002;

281   2005; 2008). Both models systematically underestimate elevation for the Little Dipper site

282   and slightly overestimate elevation for the Little River marsh, suggesting the normalisation is

283   not accurate, perhaps due to inaccuracy of the elevations for MTL and especially for HAT.

284   The UK WAT_Inv model was applied to the Wells fossil data using a correction based on the

285   average over-prediction for the Little River modern samples. No correction was applied to

286   Chezzetcook fossil samples, as no modern data were available to estimate the prediction

287   offset at this site.

288

289   **Sea-level reconstructions**

290   *Wells*

291   Tests were present in the top 19 cm of the Wells core, with only very low numbers below this

292   level (Figure 4, Table 1). Concentrations were up to 30,000 tests g^{-1}, but were generally

293   much lower at 5-13,000 tests g^{-1} and only 1000-2500 tests g^{-1} in the samples 13-16 cm

294   depth. Below 16 cm concentrations fell to 100-500 tests g^{-1} and no tests were found in a

295   sample from 22-23 cm despite counting 200 *Lycopodium* spores. For the purposes of

296   comparison with tide-gauge data, we focused on the top part of the profile which is dated to

297   the 20th century. Details of the chronological methods are given in Gehrels et al. (2002), but

298   for this site we also tested the use of SCPs for dating The SCP curve shows the first major

299   consistent presence of SCPs at about 12cm depth, dated to c. AD 1866 by extrapolating

300   between the pollen marker and the lowermost reliable ^{210}Pb ages. A mid-19th century age is

301   typical for the start of SCP curves in Europe, but this has not yet been established for North

302   America. Given the lack of sites with independently estimated ages for SCP curves, it is not

303   yet possible to use SCPs as an absolute age marker in this region. However, if adopted more

304   widely for sediment dating it would provide a valuable relative age marker and ultimately a

305   useful additional chronological tool for eastern North America.

306   In the lower part of the profile (9-16 cm depth), the testate amoeba assemblage is dominated

307   by *Centropyxis cassis* type and above 9 cm depth *Arcella catinus* type and *Difflugia pristis*

308   type are the most abundant taxa. Other more minor taxa occur throughout the profile, notably

309   other *Centropyxis* and *Difflugia* types, *Cyphoderia ampulla*, *Corythion/Trinema* types and

310   *Tracheleuglypha dentata*. All these taxa have been previously reported from this or other

311   North American marshes (Gehrels et al., 2006), with the exception of *Campascus* type,

312   previously only reported from the United Kingdom (Charman et al., 2000a).

313   With the exception of one sample, total test counts exceeded 50 for the nine

314   samples representing the 20th century, and reconstructions based on transfer functions were

315   carried out on these samples (Figure 5). All the transfer functions suggest a generally rising

316   trend in sea level through the 20th century. However, the uppermost samples suggest a

317   decline in reconstructed sea level, related to the appearance of small numbers of testate

318   amoebae typical of very high marsh or freshwater conditions (e.g. *Centropyxis arcelloides*

319   type, *Trinema lineare* type)) as well as a reduction in *Difflugia pristis* type (Figure 4). This is

320   in opposition to the trends in the tide-gauge data which suggest a slight rise or flattening in

321   sea level during this time. The local transfer function shows lower amplitude fluctuations

322   during this period and the tolerance downweighted version of the transfer function also

323   reduces the more extreme values. The bootstrapped error estimates for the testate amoebae

324   are approximately two thirds of those for the foraminifera and the tide-gauge data fall within

325   the estimated reconstruction errors for both testate amoebae and foraminifera based

326   reconstructions, with the exception of the sample from the mid-1970s. This sample has

327   consistently lower values for sea level but there were no foraminifera data available from the

328   original counts made by Gehrels et al. (2002), so that it remains uncertain whether the

329   deviation away from tide-gauge data is a result of problems with the testate amoebae data or

330   of some factor that affected the core location itself (such as localised freshwater ingress).

331   Excluding this sample, the estimated rates of sea-level rise vary between 1.62 ± 0.17 and

332   2.20 ± 0.25 mm yr^{-1} for the testate amoebae reconstructions, compared with 1.86 ± 0.12 mm

333   yr^{-1} for the tide-gauge data. Although there are a number of issues raised by the testate

334   amoebae data, clear conclusions are difficult given the relatively low sediment accumulation

335   rate and low sample numbers resulting from this (9 samples from the 20th century for testate

336   amoebae and only 5 for foraminifera).

337

338   *Chezzetcook*

339   Counts exceeding 50 tests were made down to 29 cm depth, with samples covering most of

340   the 20th century (Gehrels et al., 2005). However, obtaining counts for some of these samples

341   required counting of multiple slides with considerable input of time. Concentrations are

342   similar to those at Wells with numbers up to 25,000 tests g^{-1}, but often around 5-10,000 tests

343   g^{-1} (Figure 6). The assemblages are dominated by *Centropyxis cassis* type and *Arcella*

344   *catinus* type with lower diversity of minor taxa than at Wells. *C. platystoma* type is more

345 abundant towards the surface and *Trigonopyxis arcula* type is notable as a high marsh

346 indicator for consistent occurrence in the deeper samples.

347 　　　The reconstructions The testate amoebae-based reconstructions are very similar to

348 each other. The tolerance downweighted model reduces the amplitude of change by only a

349 small amount and the reconstruction based on the UK data is indistinguishable from the two

350 reconstructions based on North American data (Figure 7). The overall trend in the testate

351 amoebae reconstructions is very similar to changes inferred from foraminifera although the

352 gradient in the testate amoebae record is slightly steeper (3.70 ± 0.61 to 4.07 ± 1.00 mm yr^{-1}

353 compared to 3.32 ± 0.43 mm yr^{-1}). The estimated errors for individual samples in both

354 records are very similar (±5 cm). It is surprising that the errors are so similar, given that the

355 testate amoebae reconstructions are based on data from sites ranging from other parts of the

356 eastern North American coast and the United Kingdom. Whilst we would expect smaller

357 errors for a location with a small tidal range, it is surprising that these very different

358 approaches yield similar error estimates. Reconstructions are in reasonable agreement with

359 the tide-gauge record, which shows a linear trend of 3.3 ± 0.11 mm yr^{-1}. Larger short-term

360 fluctuations are shown by the foraminifera-based reconstruction than in the amoebae record.

361 While this may be partly due to the larger number of foraminifera samples analysed, the

362 short-term decline in sea level at c. AD 1955 registered by the foraminifera is at least partly

363 sampled but not reflected by the testate amoebae record. As this deflection is also not shown

364 by the tide-gauge record, it must be a result of changes only in foraminifera assemblages.

365

366 **4. Discussion**

367 ***Test concentrations and preparation***

368 The data on testate amoebae presented here and other previous studies highlight the

369 problems of separating low numbers of testate amoebae from a matrix of similar size

370 particles (Roe et al., 2002). In contrast to terrestrial peat, tests are often present in relatively

371 low concentrations and are obscured by large amounts of silt-sized organic and inorganic

372 detritus. We have attempted to increase the range of samples that can be economically

373   analysed by using a weak alkali treatment in preparation. This has been effective in

374   improving counts to statistically useful levels for the two cores presented here. While it is well

375   known that strong chemical pre-treatment such as that applied in pollen analysis can

376   selectively destroy tests (Tolonen, 1986; Hendon and Charman, 1997), short periods in weak

377   alkali (5% KOH in this case) do not appear to have this effect. Although further work on a

378   wider range of samples is still needed, the gains in analysis of salt-marsh sediments may

379   outweigh any concerns over loss or damage to tests. Counting of salt-marsh samples is still

380   more difficult than for many terrestrial peat samples and it takes considerable time (typically

381   0.5-1 day per sample) using multiple slide preparations to achieve counts >50 tests. Some

382   samples will remain impossible to count to these levels, and on the basis of the data from

383   Wells, this limit seems to be around concentrations of 1000 tests g^{-1}. It is not surprising that

384   fossil samples in these cores have relatively low concentrations because the cores are from

385   the high marsh within the zone dominated by *Balticammina pseudomacrescens* and

386   *Jadammina macrescens*, with low abundances of various other taxa (Gehrels et al., 2002,

387   2005). The Wells core is from 1.70m NGVD which is in the lowermost zone of testate

388   amoebae occurrence (Figure 2). Testate amoebae are most abundant and diverse above

389   this zone (Charman, 1998; Gehrels et al., 2001) so the core location may be sub-optimal for

390   testate amoebae populations. The Chezzetcook core is from just below HAT, so is in a better

391   position; this may be one of the reasons why the reconstruction for this site shows greater

392   agreement with the tide gauge record.

393

394   ***Regional scale transfer functions***

395   The application of the UK training set to modern and fossil North American samples shows

396   that testate amoebae zonation is sufficiently consistent over large regions such as the North

397   Atlantic, to be able to use regional scale transfer functions successfully. Elevations estimated

398   for North American modern samples using the UK transfer function are surprisingly accurate

399   (Table 3, Figure 3). Reconstructions from fossil samples show very little difference with those

400   based on the North American transfer function (Figures 5 and 7). This is in contrast to

401   foraminifera, where generally application is limited to local (Gehrels et al., 2001) or regional

402   (Horton et al., 1999b; Edwards et al., 2004) training sets. The wide geographical applicability

403   of the transfer functions suggests that they are more likely to be temporally robust than

404   transfer functions that only perform well in cross validation for single locations or small

405   regions. Whilst our data are still relatively few, these results indicate excellent potential for

406   developing large scale regional training sets in future work. Testing transfer functions by

407   application to other regions also reveals some of the problems with relying on cross-

408   validation statistics to evaluate model performance (Figure 3). Whilst extremely good

409   performance can sometimes be shown for some models such as the PLS model for the UK

410   data (Table 3), problems with systematic bias are clearly revealed when using them to

411   estimate elevations of independent samples with known elevations (Figure 3). It seems likely

412   that transfer functions that make use of residual variation in each iteration of the calibration

413   calculation (PLS, WAPLS) will be more susceptible to such problems.

414

415   ***Precision and accuracy of reconstructions***

416   One of the main aims in pursuing work on testate amoebae in salt marshes is to improve

417   precision of palaeo-sea level estimates. However, more precise reconstructions must also be

418   demonstrably accurate. Estimated sample-specific errors in fossil samples derived from

419   bootstrapping of the models based on the modern North American data are around ±5 cm for

420   Chezzetcook and ± 11 cm for Wells, the difference being due to the larger tidal range at

421   Wells. However, these error terms only include uncertainty in the relationship between

422   modern assemblages and measured elevation. They assume the relationship between fossil

423   assemblages and palaeo-elevation is the same, disregarding possible effects of changing

424   tidal regimes, disturbance, taphonomy, preservation and processing, and any other factors

425   that may have influenced the observed assemblage. Good agreement between proxies and

426   tide-gauge data in the Chezzetcook sequence suggests that these other effects are small at

427   least for the last 100 years, and thus we have greater confidence in the envelope of

428   uncertainty at this site (Figure 7). The agreement is less strong for the Wells site, although

429 low sedimentation rates and consequently low sample resolution make clear conclusions

430 difficult here (Figure 5). The similarity of error estimates for the UK and North American

431 transfer functions also supports the idea that local site factors play only a relatively minor role

432 in determining testate amoebae assemblages.

433

434 An alternative approach to assessing precision is to calculate RMSEP values based on a

435 comparison between the reconstructed values and the tide gauge data. This yields more

436 realistic error estimates than those based purely on cross validation. In this case, the

437 RMSEP values are 6.7 cm for the Wells WAT reconstruction and 3.5 cm for the Chezzetcook

438 reconstruction. Surprisingly the RMSEP values for both cores are lower than the

439 bootstrapped RMSEP values suggesting the actual error is less than that estimated from the

440 transfer function alone, and supporting the idea that bootstrapped errors can be used as a

441 reasonable conservative estimate of the average actual error in reconstructions from the pre-

442 instrumental period. However, it is also clear that some individual samples can yield

443 reconstructed values that are clearly out of line with recorded variations and, if taken at face

444 value in the fossil record, would imply rapid short-term fluctuations in past sea level. Clearly

445 estimates of past sea-level change are more robust for multi-decadal to centennial trends

446 than they are for decadal fluctuations, even where sedimentation rates allow for such high

447 resolution reconstructions.

448

449 **5. Conclusion: Improving sea-level reconstructions from testate amoebae**

450 The cores used here for analysis were initially selected to optimise results from foraminiferal

451 analysis. They are within the most stable area of the high salt marsh within the narrow zone

452 dominated by *Balticammina pseudomacrescens* and other high marsh foraminifera. In this

453 zone foraminifera are abundant at the surface and down-core. However, testate amoebae

454 are most abundant and most clearly zoned in the very uppermost parts of salt marshes

455 (Charman et al., 2001; Gehrels et al., 2006). The fossil assemblages recovered in the two

456 cores presented here are indicative of the mid to lower zones of testate amoebae occurrence

457   in marshes. There are very few of the taxa that are associated with higher locations on the

458   marsh, where zonation of assemblages is better defined because of rapid turnover of taxa

459   along the elevation gradient (Charman et al., 1998; 2002). Coring in locations at higher

460   elevations than would be used for foraminiferal analyses may yield more diverse faunas and

461   perhaps better constrained estimates of past sea levels. The setting of the highest part of the

462   marsh means that these zones are some of the best locations for sea-level reconstruction

463   because they are geomorphologically less dynamic than lower zones. Sedimentation rates

464   are likely to be stable, with continuous sediment accumulation over time. Thus, it is

465   particularly worthwhile pursuing proxy sea-level indicators such as testate amoebae in these

466   locations.

467

468   Despite the difficulties with small surface-training sets and sub-optimal core locations, the

469   Chezzetcook record shows that testate amoebae can be used to reconstruct past sea levels

470   with high precision and accuracy. The agreement with both foraminiferal reconstructions and

471   tide-gauge data shows that this technique is promising. The precision of the reconstructed

472   values is approximately ±5 cm in this microtidal location as assessed by cross validation of

473   modern training sets and somewhat lower (RMSEP 3.5 cm) when compared with tide gauge

474   data. This is similar or slightly better than the precision obtained from foraminifera, but this

475   level of precision is unusual for such studies. Furthermore, the testate amoebae data were

476   from a range of locations on the eastern North American coast and the United Kingdom,

477   suggesting testate amoebae are highly robust against local variations in the species-

478   environment relationships used to estimate past sea levels.

479

480   The nominal precision as estimated by cross validation in the Wells reconstruction is better

481   than that for foraminifera. This is likely due to the macrotidal location where foraminifera

482   zones are less tightly constrained. However, RMSEP values calculated from comparison with

483   the tide gauge records are slightly higher for testate amoebae than for foraminifera. If the

484   niches of testate amoebae taxa can be better constrained by further studies on surface

485   samples so that the accuracy of estimates is improved, higher precision estimates of past

486   sea-level change based on testate amoebae analysis will be possible at further sites. Future

487   studies should retain multi-proxy indicators as a cross check on the accuracy of

488   reconstructions, as well as utilising tide-gauge records alongside high resolution

489   reconstructions to test reconstruction methodologies. Careful evaluation of transfer functions

490   using approaches other than cross-validation of modern data sets is essential to avoid over-

491   estimating the ability of these techniques to reconstruct past changes from fossil samples.

492   Comparison with tide gauge records provides a suitable means of achieving this.

493

499

500   **References**

501   Belknap, D.F., Shipp, R.C., Stuckenrath, R., Kelley, J.T., Borns Jr., H.W., 1989. Holocene

502   sea-level change in coastal Maine. In: Anderson, W.A., Borns Jr., H.W. (Eds.),

503   Neotectonics of Maine.Maine Geological Survey Bulletin, Maine Vol. 40, pp. 85–105.

504   Bindoff N.L. et al., 2007. Observations: Oceanic Climate Change and Sea Level. In:

505   Solomon, S., et al. (Eds.), Climate Change 2007: The Physical Science Basis.

506   Contribution of Working Group I to the Fourth Assessment Report of the

507   Intergovernmental Panel on Climate Change, pp. 385-432, Cambridge University

508   Press.

509   Charman, D.J., Blundell, A., Chiverrell, R.C., Hendon, D., and Langdon, P.G., 2006.

510   Compilation of non-annually resolved Holocene proxy climate records: stacked

511   Holocene peatland palaeo-water table reconstructions from northern Britain.

512   Quaternary Science Reviews 25, 336-350.

513 Charman, D.J., Gehrels, W.R., and Roe, H. M., 2000a. The use of <63 μm fractions in the

514   separation and identification of testate amoebae in the inter-tidal zone, In: Hart, M.B.,

515   Kaminski, M. A., and Smart, C. (Eds.), Proceedings of the Fifth International

516   Workshop on Agglutinated Foraminifera: Grzybowski Foundation Special Publication,

517   v. 7, p. 89–99.

518 Charman, D.J., Hendon, D., and Woodland, W. A., 2000b. The identification of peatland

519   testate amoebae. Quaternary Research Association Technical Guide, London.

520 Charman, D.J., Roe, H.M., and Gehrels, W.R., 1998. The use of testate amoebae in studies

521   of sea-level change: a case study from the Taf estuary, South Wales, UK: The

522   Holocene, 8, 209–218.

523 Charman, D.J., Roe, H.M., and Gehrels, W.R., 2002. Modern distribution of saltmarsh testate

524   amoebae: regional variability of zonation and response to environmental variables.

525   Journal of Quaternary Science 17, 387-409.

526 Donnelly, J.P., Cleary, P., Newby, P., and Ettinger, R., 2004. Coupling instrumental and

527   geological records of sea-level change: Evidence from southern New England of an

528   increase in the rate of sea-level rise in the late 19th century. Geophysical Research

529   Letters 31, art-L05203.

530 Edwards, R.J. and Horton, B.P., 2000. Reconstructing relative sea-level change using UK

531   salt-marsh foraminifera. 169, 41-56.

532 Edwards, R.J., van de Plassche, O., Gehrels, W.R. and Wright, A.J., 2004. Assessing sea-

533   level data from Connecticut, USA, using a foraminiferal transfer function for tide level.

534   Marine Micropalaeontology 51, 239-255.

535 Gehrels, W.R., 1994. Determining relative sea-level change from salt-marsh foraminifera and

536   plant zones on the coast of Maine, U.S.A. Journal of Coastal Research 10, 990-1009

537 Gehrels, W.R., 2000. Using foraminiferal transfer functions to produce high- resolution sea-

538   level records from salt-marsh deposits, Maine, USA. Holocene 10, 367-376.

539 Gehrels, W.R., Belknap, D.F., Kelley, J.T., 1996. Integrated high-precision analyses of

540   Holocene sea-level changes: lessons from the coast of Maine. Geological Society of

541   America Bulletin 108, 1073–1088.

542 Gehrels, W.R., Belknap, D.F., Black, S., and Newnham, R.M., 2002. Rapid sea-level rise in

543   the Gulf of Maine, USA, since AD 1800. Holocene 12, 383-389.

544 Gehrels, W.R., Milne, G.A., Kirby, J.R., Patterson, R.T., Belknap, D.F., 2004. Late Holocene

545   sea-level changes and isostatic crustal movements in Atlantic Canada. Quaternary

546   International 120, 79–89.

547 Gehrels, W.R., Kirby, J.R., Prokoph, A., Newnham, R.M., Achterberg, E.P., Evans, E.H.,

548   Black, S., Scott, D.B., 2005. Onset of recent rapid sea-level rise in the western

549   Atlantic Ocean. Quaternary Science Reviews 24, 2083-2100.

550 Gehrels, W.R., Hendon, D., and Charman, D.J., 2006. Distribution of testate amoebae in salt

551   marshes along the North American East Coast. Journal of Foraminiferal Research 36,

552   201-214.

553 Gehrels, W.R., Hayward, B.W., Newnham, R.M. and Southall, K.E., 2008. A 20th century

554   sea-level acceleration in New Zealand. Geophysical Research Letters 35, L02717,

555   doi 10.1029/2007GL032632.

556 Gehrels, W.R., Roe, H.M., and Charman, D.J., 2001. Foraminifera, testate amoebae and

557   diatoms as sea-level indicators in UK saltmarshes: a quantitative multiproxy

558   approach. Journal of Quaternary Science 16, 201-220.

559 Hendon, D. and Charman, D.J., 1997. The preparation of testate amoebae (Protozoa:

560   Rhizopoda) samples from peat. Holocene 7, 199-205.

561 Holgate, S., 2007. On the decadal rates of sea-level change during the twentieth century.

562   Geophysical Research Letters 34: L01602, doi:10.1029/2006GL028492.

563 Horton, B.P., Edwards, R.J. and Lloyd, J.M., 1999a. A foraminiferal based transfer function:

564   Implications for sea-level studies. Journal of Foraminiferal Research 29, 117–129.

565 Horton, B.P., Edwards, R.J. and Lloyd, J.M., 1999b. UK intertidal foraminiferal distributions:

566   implications for sea-level studies. Marine Micropaleontology 36, 205–223.

567   Juggins, S. C2 User guide. Software for ecological and palaeoecological data analysis and

568   visualisation. 2003. Newcastle upon Tyne, University of Newcastle.

569   Kelley, J.T., Gehrels, W.R., and Belknap, D.F. 1995. Late Holocene relative sea-level rise

570   and the geological development of tidal marshes at Wells, Maine, U.S.A. Journal of

571   Coastal Research 11, 136-153

572   Patterson, R.T., and Fishbein, E., 1989. Re-examination of the statistical methods used to

573   determine the number of point counts needed for micropaleontological quantitative

574   research: Journal of Paleontology, 63, 245–248.

575   Roe H.M., Charman D.J. and Gehrels W.R., 2002. Fossil testate amoebae in coastal

576   deposits in the UK: implications for studies of sea-level change. Journal of

577   Quaternary Science 17, 411–429.

578   Rose, N. 2002 Fly-ash particles. In: Last, W.M. and Smol, J.P., (Eds.) Tracking

579   Environmental Change Using Lake Sediments. Developments in Paleoenvironmental

580   Research 2: Physical and Geochemical Methods. Springer, New York, pp. 319-349.

581   Scott, D.B., 1977. Distribution and population dynamics of marsh–estuarine foraminifera with

582   applications to relocating Holocene sea levels. Unpublished Ph.D. Thesis, Dalhousie

583   University, Halifax, Nova Scotia, Canada.

584   Scott, D.B., Boyd, R., Medioli, F.S., 1987. Relative sea-level changes in Atlantic Canada:

585   observed level and sedimentological changes vs. theoretical models. In: Nummedal,

586   D., Pilkey Jr., O.H., Howard, J.D. (Eds.), Sea Level Fluctuation and Coastal

587   Evolution. Society of Economic Paleontologists and Mineralogists Special Publication

588   41, pp. 87–96.

589   Scott, D.B., Suter, J.R. and Kosters, E., 1991. Marsh foraminifera and arcellaceans of the

590   lower Mississippi Delta: controls on spatial distributions. Micropalaeontology 37, 373-

591   92.

592   Scott, D.B., Hasegawa, S., Saito, T., Ito, K. and Collins, E., 1995a: Marsh foraminiferal and

593   vegetation distributions in Nemuro Bay wetland areas, eastern Hokkaido.

594   Transactions and Proceedings of the Palaeontological Society of Japan 180, 282-95.

595 Scott, D.B., Brown, K., Collins, E.S., Medioli, F.S., 1995b. A new sea level curve from Nova

596   Scotia: evidence for a rapid acceleration of sea-level rise in the late mid-Holocene.

597   Canadian Journal of Earth Sciences 32, 2071–2080.

598 Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores

599   13, 615-621.

600 Tolonen, K., 1986. Rhizopod analysis. In: Berglund, B.E. (Ed.), Handbook of Holocene

601   palaeoecology and palaeohydrology, pp. 645-666.

602 van de Plassche, O., van der Borg, K., de Jong, A.F.M., 1998. Sea level–climate correlation

603   during the past 1400 yr. Geology 26, 319–322.

604 Varekamp, J.C., Thomas, E. and Van de Plassche, 0., 1992. Relative sea-level rise and

605   climate change over the last 1500 years. Terra Nova 4, 293-304.

606 Woodworth, P.L., White, N.J., Jevrejeva, S., Holgate, S.J., Church, J.A. and Gehrels, W.R.,

607   2008. Evidence for the accelerations of sea level on multi-decade and century

608   timescales. International Journal of Climatology doi: 10.1002/joc.1771.

Depth (cm)	Count	T. lineare	C. dubium	D. pristis	D. pulex	D. type	P. fulva	C. Cassis	Cyphoderia	A. catinus	E.rotunda	Unknown	Total
8-9	29	1.9		7.8	3.9	11.7			1.9	27.2		1.9	56.4
16-17	6							1.2		4.6		1.2	7.0
24-25	4			2.8			5.6	2.8					11.2
31-32	3		6.0					6.0				6.0	18.1
40-41	1											4.9	4.9
48-49	3									4.9			4.9
57-58	6					2.6	2.6			2.6			7.9
65-66	8					1.9				5.7			7.6
Total	60	1.9	6.0	10.6	3.9	16.2	8.2	10.0	1.9	45.1	0.0	14.0	117.9

5% KOH

Depth (cm)	Count	T. lineare	C. dubium	D. pristis	D. pulex	D. type	P. fulva	C. Cassis	Cyphoderia	A. catinus	E.rotunda	Unknown	Total
8-9	41			23.3	5.8				5.8	44.7			79.7
16-17	13			4.6					3.5	7.0			15.1
24-25	12			8.4		2.8		8.4			8.4	5.6	33.5
31-32	4	6.0				12.1						6.0	24.2
40-41	0												
48-49	0												
57-58	1						1.3						1.3
65-66	0												
Total	71	6.0	0.0	36.3	5.8	14.9	1.3	8.4	9.3	51.7	8.4	11.6	153.7

Table 1: Testate amoebae counts from standard (upper) and KOH-based (lower) sample pre-treatment for eight samples from the Wells core. Total no.tests counted in left hand column. All other figures are concentrations (nos. mg^{-1} wet weight sample).

Model	r^2	Average bias	Max. bias	RMSEP
WA_Inv	0.84	-0.0027	0.104	0.053
WA_Cla	0.85	-0.0034	0.084	0.054
WAT_Inv	0.80	-0.0047	0.123	0.059
WAT_Cla	0.81	-0.0055	0.099	0.060
PLS	0.81	-0.0011	0.095	0.057
MAT	0.78	-0.0173	0.166	0.068
WMAT	0.80	-0.0120	0.124	0.061

Table 2: Transfer function performance in cross validation using the leave one out (jack-knifing) method for the North American testate amoebae data. Results of WAPLS were the same as for simple weighted averaging and are not shown here. RMSEP (Root mean squared error of prediction) and bias data are for elevation normalised to the difference between mean tide level and highest astronomical tide.

Model and application	r^2	RMSEP
a) Cross validation		
WA_Inv (Weighted average, inverse deshrinking)	0.41	0.076
WA_Cla (Weighted average, classical deshrinking)	0.43	0.098
WAT_Inv (Tolerance downweighted weighted average, inverse deshrinking)	0.45	0.074
WAT_Cla (Tolerance downweighted weighted average, classical deshrinking)	0.47	0.104
WAPLS Component 3 (Weighted average partial least squares)	0.42	0.077
PLS Component 5 (Partial least squares)	0.99	0.012
MAT (Modern analogue)	0.44	0.074
WMAT (Weighted modern analogue)	0.61	0.063
b) Applied to US data		
WAT_Inv		0.083
PLS Component 5		0.101

Table 3: Model performance results for the UK testate amoebae data; a) in cross validation using normalised (MTL-HAT) data, b) applied to normalised modern US data. , c) applied to actual elevation above MTL for individual sites. For b) and c), the RMSEP is calculated on the errors between the observed and predicted values shown in Figure 3, not on the linear trend lines shown.

Figure captions

Figure 1: Locations for the core sites. See Gehrels et al. (2006) and Charman et al. (2002) for details of modern sampling sites.

Figure 2: Modern testate amoebae data plotted against elevation from the marshes used in the North American transfer function. a) Little River marsh, Wells, Maine, b) Little Dipper Harbour Marsh, New Brunswick. The tidal data shown on the height axis are highest astronomical tide (HAT) and mean highest high water (MHHW). HF is the maximum height of foraminifera recorded in the 63-500 µm size range. .

Figure 3: Comparison between observed sample elevations for the modern North American samples and their predicted elevations based on the UK transfer function applied to the testate amoebae assemblages. a) For all samples plotted as elevation normalised for tidal range (MTL-HAT). b) and c) For untransformed elevations in height above MTL, b) Little River and c) Little Dipper Harbour. Circles – Little River, Squares – Little Dipper, Open – PLS model, Closed – WAT model. Linear regression lines shown as black (Little River) and grey (Little Dipper). Grey dashed line – 1:1 line.

Figure 4: Testate amoebae diagram for core FS-1, Wells, showing all samples, including those with low total counts. A further sample at 22.5 cm contained no testate amoebae or foraminifera. The estimated ages are shown with 2σ errors based on ^{210}Pb analyses.

Figure 5: Comparison between reconstructions for the Wells core based on testate amoebae, foraminifera and the tide gauge record from Portland, Maine (grey symbols). The rates of sea-level change are the linear trends over the period covered by the tide-gauge record. The rates for testate amoebae exclude the sample from the mid-1970s which gives consistently

lower values and is not represented in the foraminifera samples. For comparison, the linear trend of the tide-gauge record is 1.86 ± 0.12 mm yr^{-1}. Vertical error bars are RMSEP from transfer functions. Age error bars are 2σ errors from age-depth model. No RMSEP values calculated for c) because of the low number of samples (n=17) in the local training set.

Figure 6: Testate amoebae % diagram from Chezzetcook core CZ-25.

Figure 7: Sea level reconstructions based on testate amoebae and foraminifera from Chezzetcook Marsh compared to the tide gauge record from Halifax (grey symbols). The rates of sea-level change are the linear trends over the period covered by the tide-gauge record. For comparison, the linear trend of the tide-gauge record is 3.30 ± 0.11 mm yr^{-1}. Vertical error bars are RMSEP from transfer functions. Age error bars are 2σ errors from age-depth model.
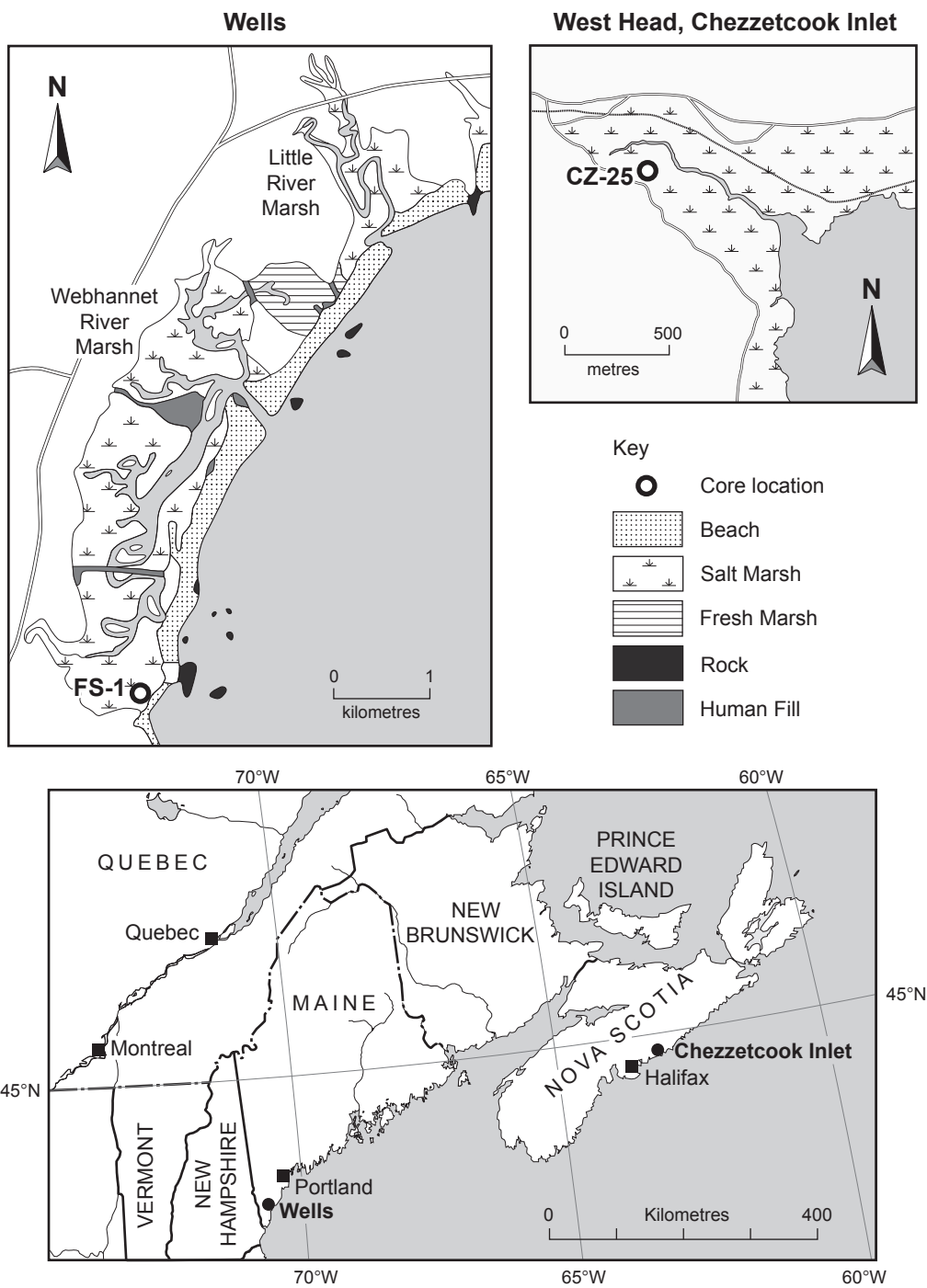
Figure 2
Click here to download Figure: Figure 2.doc

a)

Little River marsh, Wells, Maine
Testate amoebae

b)
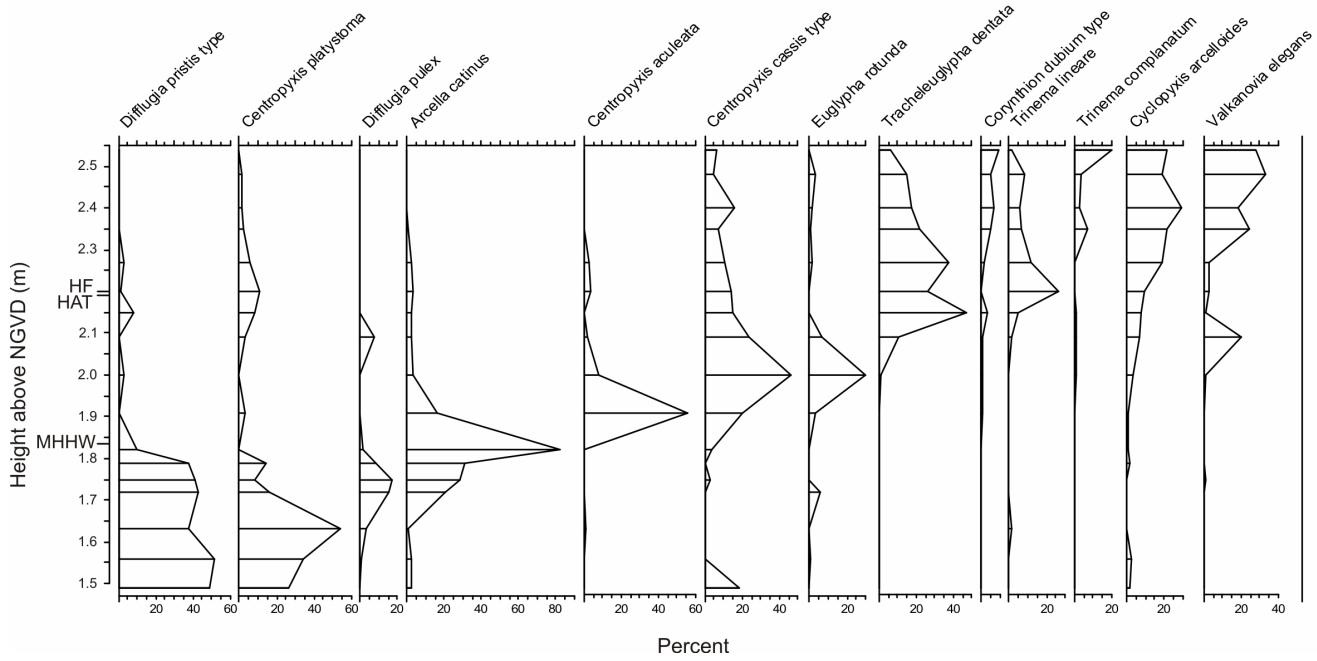
Little Dipper Harbour marsh, New Brunswick
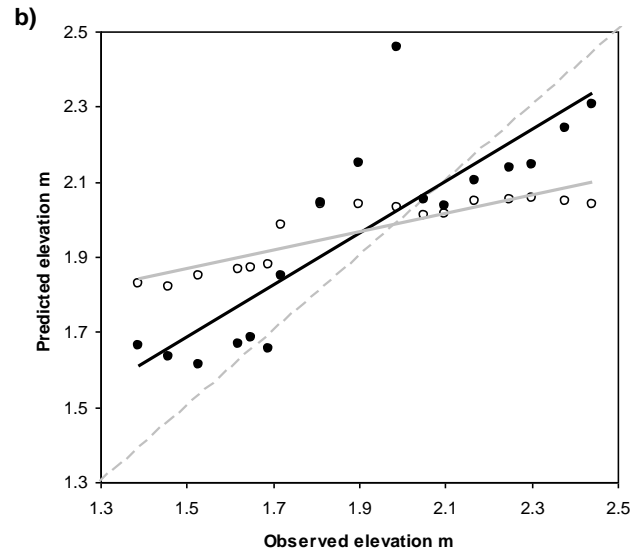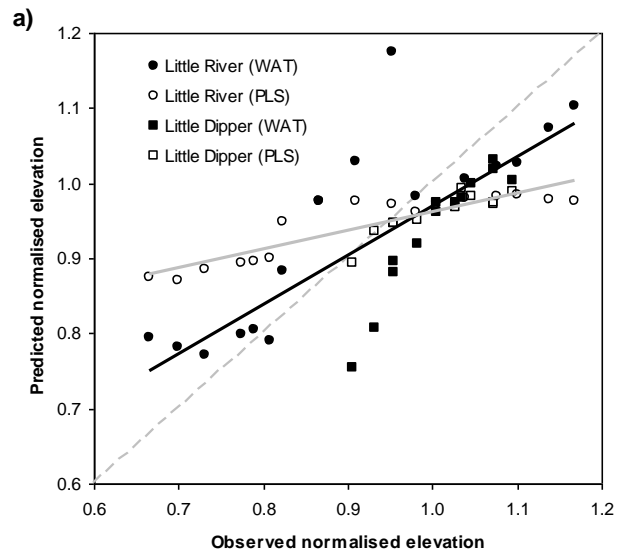Testate amoebae
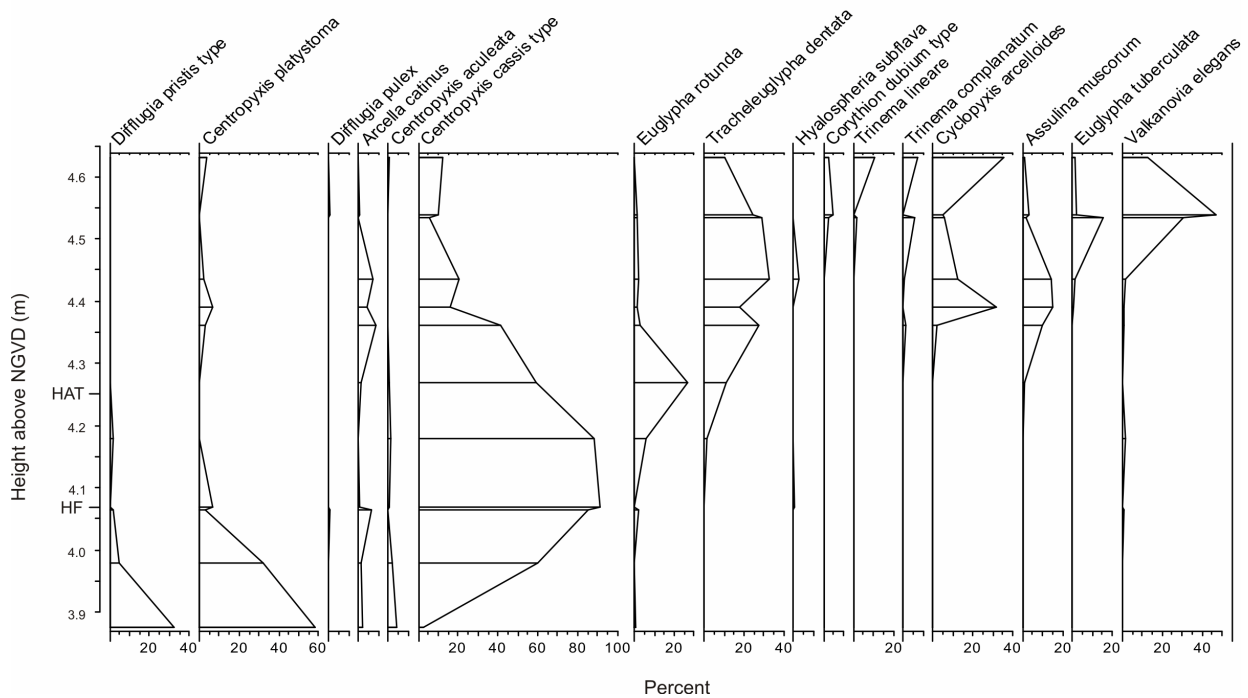
Figure 3
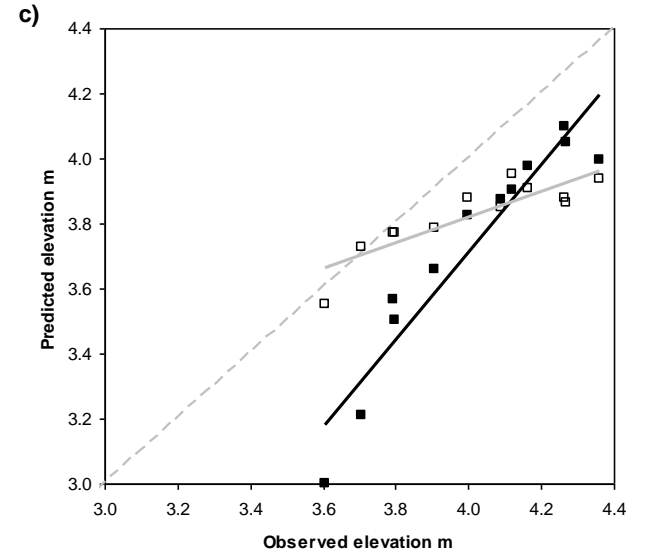
Figure 4
Click here to download Figure: Figure 4.doc
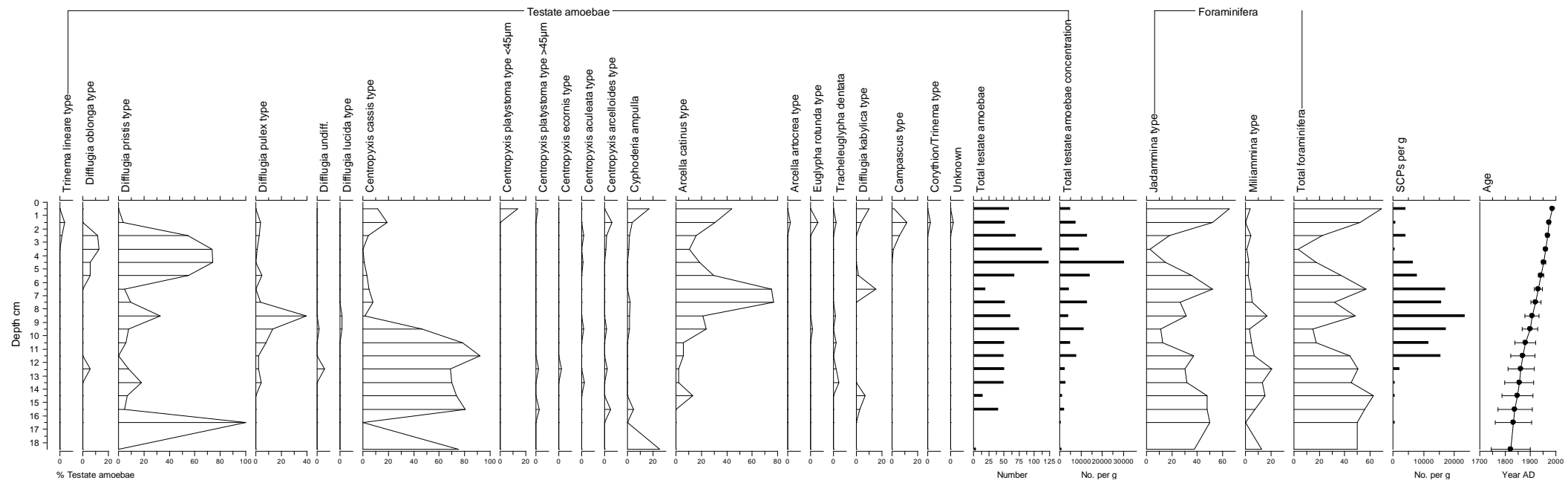
Figure 5
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Figure 5

a) Weighted average
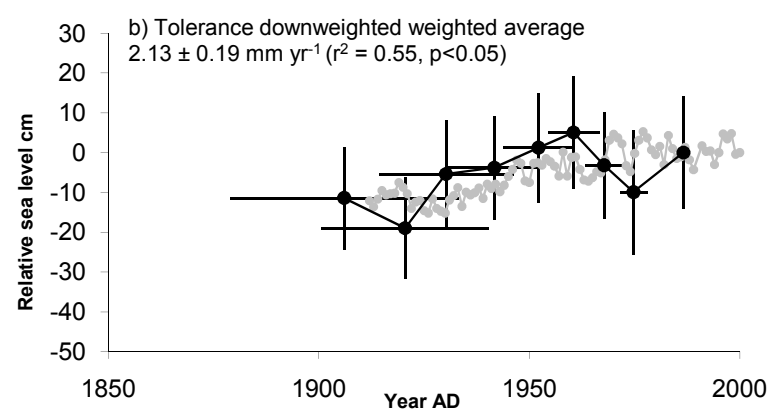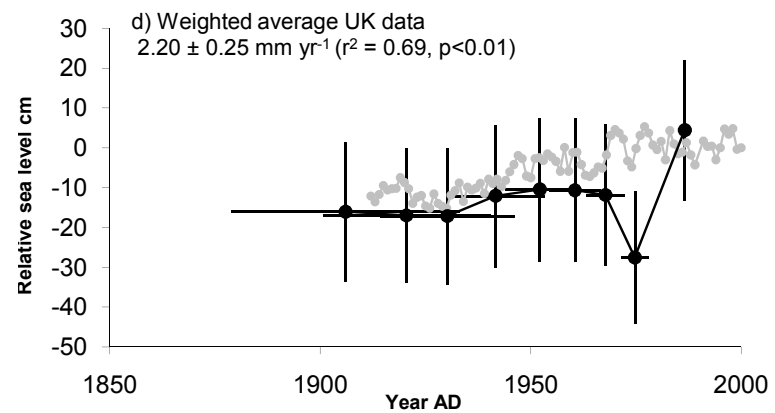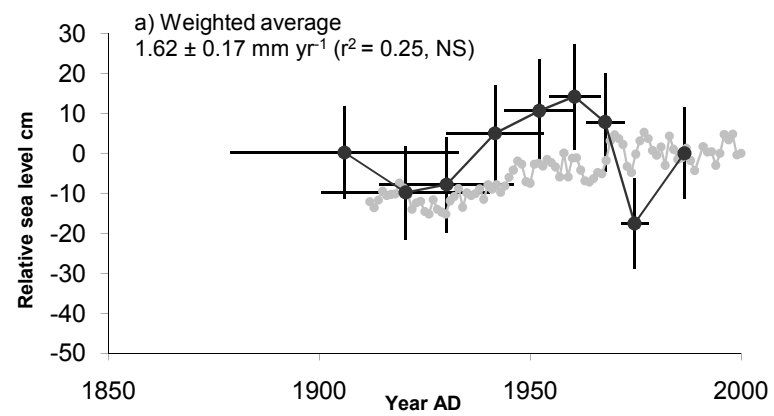1.62 ± 0.17 mm yr^{-1} (r^2 = 0.25, NS)

b) Tolerance downweighted weighted average
2.13 ± 0.19 mm yr^{-1} (r^2 = 0.55, p<0.05)

c) Weighted average (local transfer function)
1.69 mm yr^{-1} (r^2 = 0.56, p<0.01)

d) Weighted average UK data
2.20 ± 0.25 mm yr^{-1} (r^2 = 0.69, p<0.01)
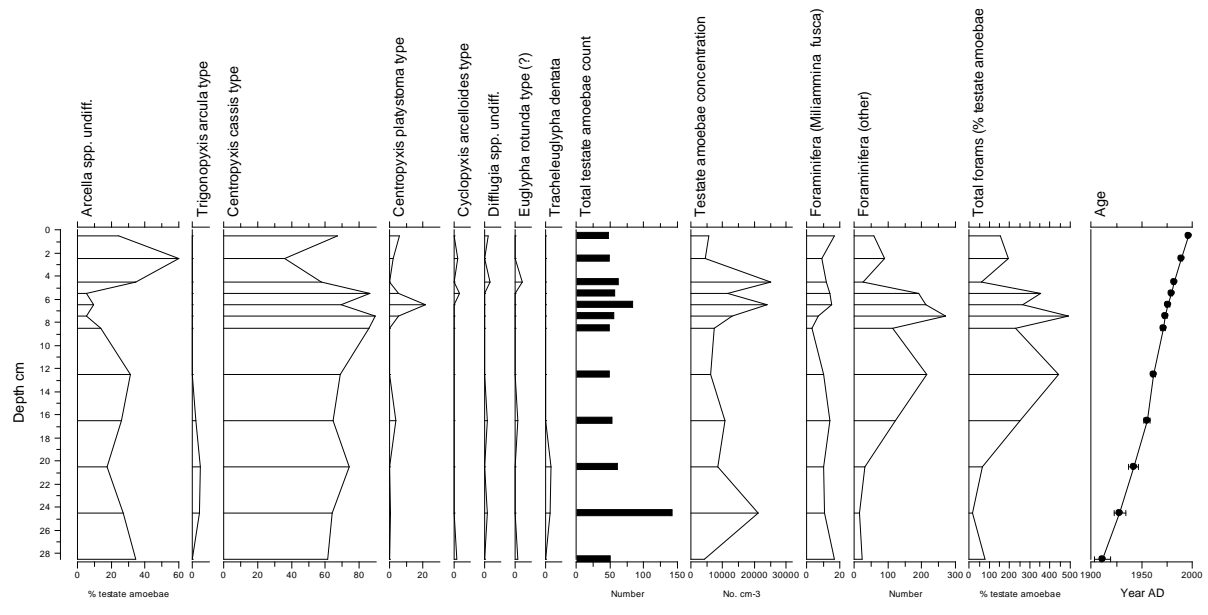
e) Foraminifera (Gehrels et al., 2002)
1.9 mm yr^{-1} (r^2 = 0.90, p<0.01)
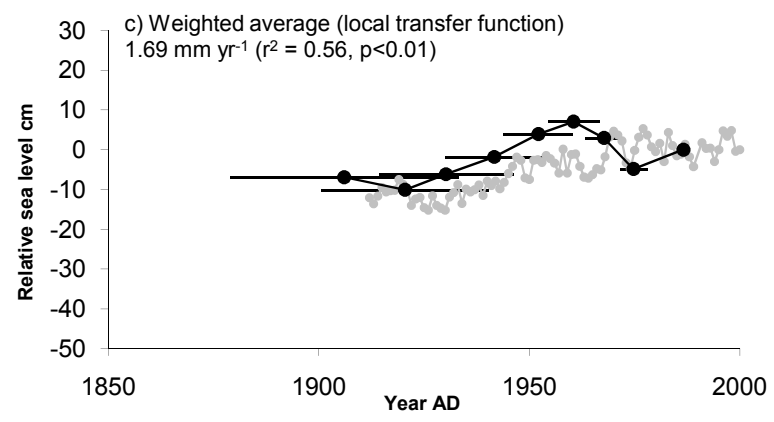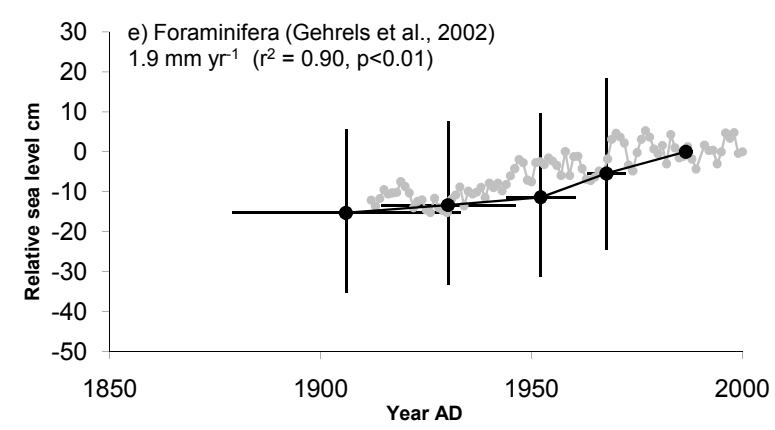
Figure 6
Click here to download Figure: Figure 6.doc

a) Weighted average - 3.70 ± 0.61 mm yr^{-1} ($r^2 = 0.92$, p<0.001)

b) Tolerance downweighted weighted average - 3.70 ± 0.70 mm yr^{-1} ($r^2 = 0.93$, p<0.001)

c) Weighted average UK data - 4.07 ± 1.00 mm yr^{-1} ($r^2 = 0.94$, p<0.001)

a) Foraminifera - 3.32 ± 0.43 mm yr^{-1} ($r^2 = 0.94$, p<0.001)