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Research paper

Applicability of transfer functions for relative sea-level reconstructions in the southern North Sea coastal region based on salt-marsh foraminifera

Katharina Müller-Navarra[a,*], Yvonne Milker[a,b], Gerhard Schmiedl[a]

[a] University of Hamburg, Center for Earth System Research and Sustainability, Institute for Geology, Bundesstraße 55, 20146 Hamburg, Germany
[b] University of Leipzig, Institute of Geophysics and Geology, Talstraße 35, 04109 Leipzig, Germany

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ABSTRACT

We studied the foraminiferal distribution in two naturally grown salt marshes from the southern North Sea with respect to the tidal frame, salinity, grain size and pH. The salt marshes are situated on the landward sides of the islands of Sylt (Rantum, Germany) and Fanø (Sønderho, Denmark). In both study areas, foraminifera have a vertical distribution with respect to water level, but also show inter-site variability, which can be related to environmental differences (e.g., in salinity and pH) and different flooding dynamics of the coastal salt marsh (Rantum) and the tidal-creek salt marsh (Sønderho). We developed different transfer functions, based on the widely applied standardized water level index (SWLI) approach and on three flooding parameters (duration of submergence (DoS), mean submergence time (MST), and flooding frequency (FF)), in order to assess their predictive ability for relative sea-level estimates for the southern North Sea coastal region. The water-level data used for these approaches are determined based on local water-level conditions, corrected for tidal distortions using water-level measurements for the Sønderho salt marsh and the Rantum tide gauge. The SWLI approach shows a precision (root mean squared error of prediction (RMSEP) of 0.23 m), which is around 15% of the tidal range. All three flooding approaches show comparable results at around mean tide level to mean high water, while at higher elevations, foraminiferal distribution becomes non-linearly correlated to flooding parameters resulting in lower precision of > 1.0 m. Our results suggest that the SWLI approach performs well and that the flooding approaches offer a suitable addition for assessing relative sea-level estimates in the North Sea region. We enhanced the knowledge on changing precision for tide level reconstructions along the elevational gradient in a storm dominated tidal area where elevation and flooding parameters are non-linear correlated.

1. Introduction

Salt marshes represent the tidally influenced transition zone between marine and terrestrial ecosystems and are important habitats with characteristic plant and animal life. They are natural buffering zones against tides and storm surges, and hence are a valuable component of coastal protection in connection with relative sea-level rise (Möller et al., 2014). In this context, the vertical development and lateral shift of salt marshes in relation to long-term changes of relative sea level need to be better understood (Van de Plassche et al., 1992; Kirwan and Murray, 2007; Deegan et al., 2012; Balke et al., 2016; Kirwan et al., 2016).

One aspect in understanding salt-marsh development is to study salt-marsh foraminifera and their relation to the tidal influence. It has been shown that in natural salt marshes certain species are found in specific zones relative to the tidal frame (e.g., Horton and Edwards, 2006). This vertical distribution of salt-marsh foraminifera with respect to the tidal frame is controlled by changing environmental parameters such as pH, salinity and grain size (e.g., Phleger, 1970; Horton and Edwards, 2006; Hawkes et al., 2011) or by food availability (Shaw et al., 2016). Scott (1977) reported that individual foraminiferal species occur in a characteristic and limited range of habitats around their particular environmental optimum. The first recognition of this relationship dates back to the work of Phleger and Walton (1950) and Phleger (1954), who studied salt-marsh foraminifera from Massachusetts and the Mississippi Delta area. They described the restriction of certain indigenous species to marsh areas and stated that salt-marsh foraminifera can be used to reconstruct the history of old salt marshes. Two decades later, Scott (1976) and Scott and Medioli (1978) used salt-marsh foraminifera as proxies to reconstruct former tide levels in Nova Scotia, North America. Scott (1977) concluded that foraminiferal assemblages could be used to accurately locate tidal datums (e.g., mean high water) in a marsh sequence. Since the first observations, this relationship has been confirmed in many studies around the world. In

* Corresponding author.
E-mail address: Katharina.mueller-navarra@uni-hamburg.de (K. Müller-Navarra).

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more recent times, foraminifera-based transfer functions are widely applied to reconstruct relative sea-level changes by using elevation relative to the local tidal frame as a proxy for sea level in salt marshes. Such transfer functions were initially applied by Imbrie and Kipp (1971) and were for example also used to reconstruct paleoenvironmental changes in lakes using diatoms to reconstruct pH (Renberg and Hellberg, 1982). Guilbault et al. (1995) were the first who used transfer functions to reconstruct paleo-elevations based on foraminifera in a salt marsh at Vancouver Island (Canada). Ter Braak and Prentice (1988) were the first to use unimodal-based Weighted Averaging (WA) techniques and Ter Braak and Juggins (1993) introduced a combination of unimodal (WA) and linear partial least squares (PLS) methods to improve the performance of transfer functions. These methods were subsequently applied in a number of studies, confirming the applicability of intertidal foraminifera for relative sea-level reconstructions, e.g. in the UK (Gehrels, 1999; Horton et al., 1999; Barlow et al., 2013), at the US Atlantic coast (Gehrels, 2000; Edwards et al., 2004; Engelhart and Horton, 2012; Kemp et al., 2012; Kemp et al. 2017a,b), at the Atlantic coast of SW Europe (Leorri et al., 2010), at the North Sea coast (Gehrels and Newman, 2004), in Iceland (Gehrels et al., 2006), in Tasmania (Callard et al., 2011), in southern Africa (Strachan et al., 2015), and along the Adriatic Sea (Shaw et al., 2016). Until today, the establishment of a regional transfer function for the southern North Sea region is hampered by the rare occurrence of naturally developed coastal ecosystems. Most salt marshes and the associated floral and faunal zonation of this region were largely altered in the past by anthropogenic impacts such as draining and sheep grazing (Müller-Navarra et al., 2016). Since the establishment of the Wadden Sea National Park in 1985, protected salt marshes are able to develop more naturally again.

It has been argued that the duration of submergence, which is a function of elevation relative to the tidal frame and the height of the tides reaching this elevation, determines the foraminiferal distribution in salt marshes (Van der Molen, 1997; Horton and Edwards, 2006; Balke et al., 2016). However, the local tidal-induced duration of submergence has been rarely addressed in salt-marsh studies although Horton and Edwards (2006) and others stated that information about the local tidal regime may improve the resolution of reconstructions of the local relative sea level by reducing scatter in the modern taxa-elevation relationships and that sample elevation can be considered to be a general indicator of flooding frequency. Gehrels (2000) and Gehrels et al. (2001) used the flooding and height normalization for their training data sets but found a moderate correlation between flooding duration and the modern foraminiferal distribution in southern UK and Maine (USA) salt marshes; however, the relationship improved significantly when other microfossil groups (diatoms and amoebae tests) were included. Further, Kemp and Telford (2015) reported a non-linear relationship between elevation and tidal inundation in the highest marsh. And Wright et al. (2011) discussed the difficulties obtaining information on local tidal datums and developed the principle of the highest occurrence of foraminifera (HOF) to avoid problems concerning the local tidal information, especially at elevations in the upper tidal regime. These results underline the necessity to quantify the influence of local flooding and tide level on the foraminiferal distribution and to test the usefulness of these parameters for relative sea-level reconstructions.

The aim of our study is to develop a first regional transfer function for the southern North Sea coastal region that can be used to reconstruct past relative sea-level changes in southern North Sea salt marshes. For this, we investigated the foraminiferal distribution along four surface transects in two recently naturally-grown back-barrier island salt marshes in the southern North Sea region and calculated duration of local-scale submergence, flooding frequency, and submergence time based on local tide gauge data. We developed and compared different regional transfer functions by using the widely applied standard water level index (SWLI) approach and approaches based on the flooding parameters duration of submergence (DoS), mean submergence time (MST), and flooding frequency (FF) to quantify the relationship between the foraminiferal distribution, elevation within the tidal frame, and flooding parameters. We further address the difficulties in depicting the local tidal conditions in each salt marsh, by using tidal datums from permanent tide gauges installed in the direct vicinity.

2. Regional setting

The southern North Sea coast encompasses Europe's largest intertidal region including major areas of salt marshes, and remains one of the largest widely natural lowland ecosystem (Bakker et al., 2002). In the southern North Sea coastal region basically two distinct types of salt marshes exist. The German and Dutch coasts are mainly characterized by anthropogenically altered open-coast mainland marshes with artificial drainage systems. These typically muddy or sandy systems are characterized by a flat topography, show relatively little biotic variation, and adjoin exposed tidal flats (Pye and French, 1993). In contrast, the Frisian Islands are mainly characterized by almost naturally-developed sandy to muddy open-coast and estuarine back-barrier marshes with meandering tidal creeks, located on the sheltered, landward sides of coastal barrier islands and spits. These marshes are characterized by a relatively high degree of biotic variation and form about 40% of the total marsh area in the Wadden Sea. Because an earlier study has shown that the anthropogenically influenced mainland salt marshes are not suitable for relative sea-level studies (Müller-Navarra et al., 2016), we concentrate on the naturally grown back barrier island salt marshes in this study.

We selected two salt-marsh areas, located on the protected landward sides of Sylt and Fanø islands, including a coastal salt marsh at Rantum (Sylt) and a tidal-creek salt marsh at Sønderho (Fanø) (Fig. 1). Both regions are microtidal and are characterized by predominantly semidiurnal tides (Table 1). In the following, we characterize the study areas in greater detail.

2.1. Rantum (Sylt)

The island of Sylt is the largest North Frisian Island, located along the northeastern part of the German North Sea coast (Fig. 1). Postglacial Holocene sea-level rise, longshore currents and isostatic vertical movements determine the shape of this island (Bayerl and Higelke, 1994). Its west side, open to the North Sea, is strongly influenced by erosional processes that affect the beaches due to storms, storm floods, tides, longshore currents and breaking waves (Lamprecht, 1957). In contrast, the eastern side is protected from erosional processes, allowing sediment to accumulate. The studied open-coast back barrier salt marsh region is situated at the southeastern end of the island, near the small village of Rantum (Fig. 1). The study area is situated in front of dunes and fringes and has an N-S extension of around 1 km length and a W-E extension of around 100 m. The Rantum salt marsh can be divided into high marsh, middle marsh and low marsh zones on the basis of vascular plants. The vegetation of the high marsh is dominated by *Agrostis stolonifera* and *Festuca rubra* with a few *Limonium vulgare*. The middle marsh is dominated by *Atriplex portulacoides* and the low marsh by *Salicornia europaea*.

2.2. Sønderho (Fanø)

The island of Fanø is located in the Danish North Sea region. The island is a natural reserve. The sandy sediments forming beaches on the west-coast of Fanø originate partly from the northern end of Sylt (Davis, 1994) and generate a seaward progradation of the coast of Fanø (Davis, 1994). A further dune line with vegetation cover is growing at the beach side. The studied tidal-creek salt marsh of Sønderho is situated on the southern edge of the island, in the direct vicinity of the urban area of Sønderho, in front of a dike (Fig. 1). It has an N-S extension of around