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Sea-level changes in Iceland and the influence of the North Atlantic Oscillation during the last half millennium

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ABSTRACT

We present a new, diatom-based sea-level reconstruction for Iceland spanning the last ~500 years, and investigate the possible mechanisms driving the sea-level changes. A sea-level reconstruction from near the Icelandic low pressure system is important as it can improve understanding of ocean–atmosphere forcing on North Atlantic sea-level variability over multi-decadal to centennial timescales. Our reconstruction is from Viðarhólmi salt marsh in Snæfellsnes in western Iceland, a site from where we previously obtained a 2000-yr record based upon less precise sea-level indicators (salt-marsh foraminifera). The 20th century part of our record is corroborated by tide-gauge data from Reykjavik. Overall, the new reconstruction shows ca 0.6 m rise of relative sea level during the last four centuries, of which ca 0.2 m occurred during the 20th century. Low-amplitude and high-frequency sea-level variability is superimposed on the pre-industrial long-term rising trend of 0.65 m per 1000 years. Most of the relative sea-level rise occurred in three distinct periods: AD 1620–1650, AD 1780–1850 and AD 1950–2000, with maximum rates of ~3 ± 2 mm/yr during the latter two of these periods. Maximum rates were achieved at the end of large shifts (from negative to positive) of the winter North Atlantic Oscillation (NAO) Index as reconstructed from proxy data. Instrumental data demonstrate that a strong and sustained positive NAO (a deep Icelandic Low) generates setup on the west coast of Iceland resulting in rising sea levels. There is no strong evidence that the periods of rapid sea-level rise were caused by ocean mass changes, glacial isostatic adjustment or regional steric change. We suggest that wind forcing plays an important role in causing regional-scale coastal sea-level variability in the North Atlantic, not only on (multi-)annual timescales, but also on multi-decadal to centennial timescales.

1. Introduction

Determining the nature and causes of sea-level variability in the pre-industrial era provides a long-term context for comparing recent sea-level trends and for developing future projections (e.g. Van de Plassche, 2000; Gehrels et al., 2004; Milne et al., 2009; Kemp et al., 2011; Barlow et al., 2012). Driving mechanisms of sea-level changes include mass changes in land-based ice, and other processes such as steric expansion and contraction, and dynamic oceanographic processes including variations in wind stress and atmospheric pressure (Gehrels and Woodworth, 2013).

Unravelling the relative importance of these processes on multi-decadal to centennial timescales requires the development of precise proxy-based sea-level reconstructions that extend before the start of instrumental observations, with good age (decadal) and height (sub-decimetre) control. In the North Atlantic, the most precise reconstructions are developed along low-energy coastlines with small tidal ranges where organic-rich salt marshes provide environments that are suitable for developing continuous sea-level records over the last few millennia (e.g. Gehrels et al., 2005; Kemp et al., 2011).

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Identifying the drivers of regional sea-level change demands multiple observations from different parts of any particular ocean basin, which by necessity will be from a variety of depositional and tidal range environments (Long et al., 2014). A variety of microfossil types that include foraminifera, testate amoebae and diatoms are typically used, on their own or occasionally in combination, to constrain palaeomarsh surface elevations and past sea-level changes (e.g. Gehrels et al., 2001; Kemp et al., 2009; Charman et al., 2010; Barlow et al., 2013).

In this paper we develop a new relative sea-level (RSL) reconstruction from a meso-tidal salt marsh in western Iceland, an area particularly susceptible to wind-driven sea-level variability due to its location in the pathway of low pressure systems. In a previous paper Gehrels et al. (2006) reconstructed a 2000-yr record from this site using foraminifera (Fig. 1), and identified a single acceleration in sea level that was dated to the beginning of the nineteenth century. However, the record was heavily dominated by the upper marsh species *Jadammina macrescens* with occasional *Paratrochammina* (*Lepidoparatrochammina*) *haynesi*. This low species diversity provided limited constraints on the elevation of the formation of the past marsh surface, making it impossible to identify any fluctuations in relative sea-level change beyond the 19th century inflection. Here we revisit the study site, Viðarhólmi salt marsh, and focus in on the last five centuries. We exploit the greater sensitivity to elevation (and hence sea level) of diatoms to produce a ~500-yr sea-level reconstruction of high vertical precision. We also apply new chronological analyses to the upper part of the stratigraphic section previously studied to generate an improved age model using new tephra and AMS ^{14}C dates, in combination with previous AMS ^{14}C, ^{137}Cs and chemostratigraphical analyses. The resulting reconstruction identifies three distinct periods of rapid sea-level rise during the last ~500 years.

To assess the potential drivers behind these changes we compare the new record to proxy and instrumental reconstructions of the North Atlantic Oscillation (NAO) Index over the same interval. The NAO exerts a strong influence over regional wind patterns, precipitation and temperature, mainly in the winter (e.g. Hurrell et al., 2003). The influence of (winter) NAO (wNAO) on Atlantic sea level during the instrumental era is well established (Andersson, 2002; Woolf et al., 2003; Tsimplis et al., 2005, 2006; Kolker and Hameed, 2007; Miller and Douglas, 2007; Woodworth et al., 2007; Haigh et al., 2010), but its significance in controlling dynamic sea-level variability over longer time intervals has not previously been explored. In this paper we present proxy evidence of at least two pre-industrial oscillations in sea level that broadly correlate to changes in reconstructed wNAO in the North Atlantic Ocean, highlighting the influence of ocean–atmosphere forcing on regional-scale sea-level variability during past centuries.

2. Study area

Viðarhólmi salt marsh (64.77°N, 22.42°W) is located on the west coast of Iceland (Fig. 1) in an area that has been seismically stable during the late Holocene (Angelier et al., 2004). Árnadóttir et al. (2009) estimate modest rates of uplift due to GIA (~1 mm/yr) in the period AD 1993–2004 based on GPS observations, but Gehrels et al. (2006) documented 1.3 m of relative sea-level rise during the last 2000 years, indicating that on millennial time scales this coastal area is subsiding. The marsh is underlain by Tertiary basalt (Ward, 1971), and protected by a barrier spit to the south and by an outcropping Holocene lava flow to the east. Several tidal channels dissect the salt marsh. Our fossil sediment section is taken from the cleaned face of one of these channels where a 2 m high peat section is exposed (Figs. 1 and 2). This is the same section where monoliths for the Gehrels et al. (2006) study had been taken in 2001 and 2003. Today the salt marsh is largely undisturbed by human influence but is occasionally grazed by sheep. Dominant plants on the marsh are *Carex lyngbyei*, *Agrostis stolonifera*, *Festuca rubra* and *Puccinellia maritima* (Ingólfsson, 1998). Mean tidal range at Viðarhólmi is 2.1 m, mean sea level (MSL) is 0.12 m above the Iceland geodetic

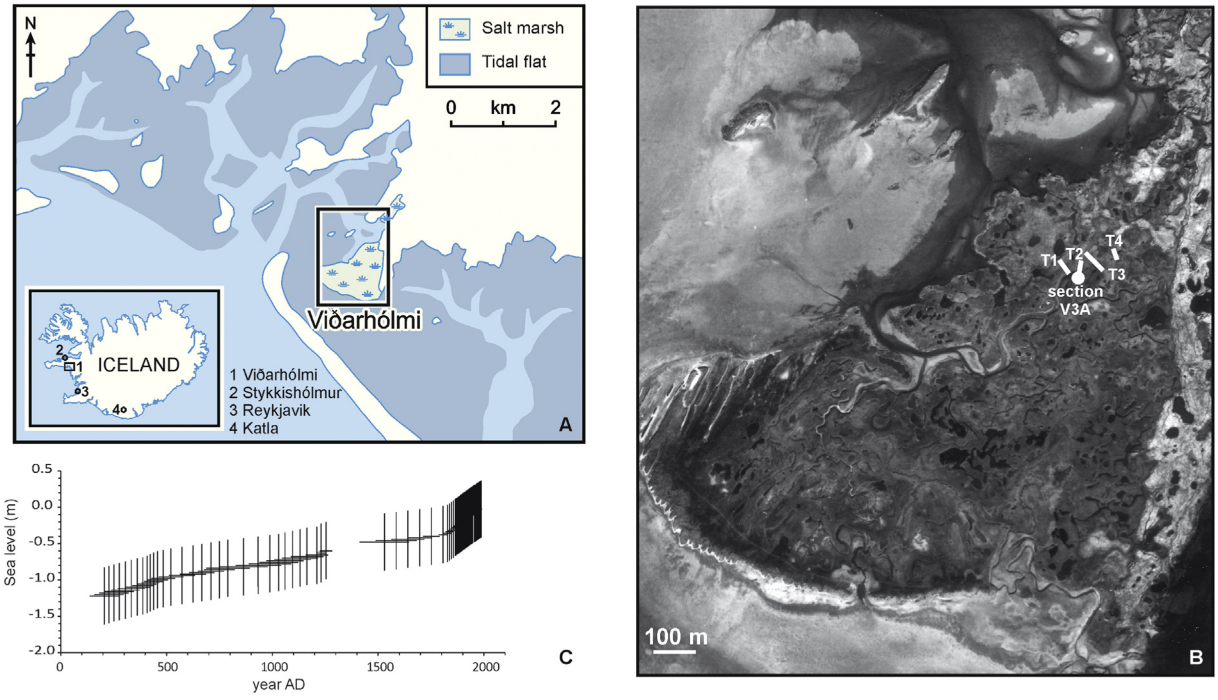

Fig. 1. Location map and previous work. A: Regional map showing location of study site (Viðarhólmi) and other locations mentioned in text. B: Aerial photograph of Viðarhólmi salt marsh showing location of surface sample transects (T1–4) and sampled section V3A. C: Foraminifera-based sea-level reconstruction for Viðarhólmi salt marsh, with 2σ error bars, spanning the last 2000 years from Gehrels et al. (2006).