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

Margot H. Saher^{1*}, W. Roland Gehrels², Natasha L.M. Barlow³, Antony J. Long³, Ivan D.
 Haigh⁴ and Maarten Blaauw⁵

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6¹School of Ocean Sciences, Bangor University, Menai Bridge LL59 5AB, UK; ²Environment 7Department, University of York, Heslington, York YO10 5DD, UK; ³ Department of 8Geography, Durham University, South Road, Durham DH1 3LE, UK; ⁴Ocean and Earth 9Science, National Oceanography Centre, University of Southampton, European Way 10Southampton, SO14 3ZH, UK; ⁵School of Geography, Archaeology and Palaeoecology, 11Queen's University Belfast, Elmwood Avenue, Belfast BT7 1NN, UK.

12*Corresponding author (email: <u>m.saher@bangor.ac.uk</u>, tel: 0044 1248 383819, fax: 0044 131248 716367)

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15Abstract

16We present a new, diatom-based sea-level reconstruction for Iceland spanning the last ~500 17years, and investigate the possible mechanisms driving the sea-level changes. A sea-level 18reconstruction from near the Icelandic low pressure system is important as it can improve 19understanding of ocean-atmosphere forcing on North Atlantic sea-level variability over multi-20decadal to centennial timescales. Our reconstruction is from Viðarhólmi salt marsh in 21Snæfellsnes in western Iceland, a site from where we previously obtained a 2000-yr record 22based upon less precise sea-level indicators (salt-marsh foraminifera). The 20th century part of 23our record is corroborated by tide-gauge data from Reykjavik. Overall, the new 24reconstruction shows ca. 0.6 m rise of relative sea level during the last four centuries, of 25which ca. 0.2 m occurred during the 20^{th} century. Low-amplitude and high-frequency sea-26level variability is super-imposed on the pre-industrial long-term rising trend of 0.65 m per 271000 years. Most of the relative sea-level rise occurred in three distinct periods: AD 1620-281650, AD 1780-1850 and AD 1950-2000, with maximum rates of $\sim 3 \pm 2$ mm/yr during the 29latter two of these periods. Maximum rates were achieved at the end of large shifts (from 30negative to positive) of the winter North Atlantic Oscillation (NAO) Index as reconstructed 31from proxy data. Instrumental data demonstrate that a strong and sustained positive NAO (a 32deep Icelandic Low) generates setup on the west coast of Iceland resulting in rising sea 33levels. There is no strong evidence that the periods of rapid sea-level rise were caused by 34ocean mass changes, glacial isostatic adjustment or regional steric change. We suggest that 35wind forcing plays an important role in causing regional-scale coastal sea-level variability in 36the North Atlantic, not only on (multi-)annual timescales, but also on multi-decadal to 37centennial timescales.

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39Key words: diatoms, ocean dynamics, Iceland, Little Ice Age, sea-level rise, NAO

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421 Introduction

43Determining the nature and causes of sea-level variability in the pre-industrial era provides a 44long-term context for comparing recent sea-level trends and for developing future projections 45(e.g. Barlow et al., 2012; Gehrels et al., 2004; Kemp et al., 2011; Milne et al., 2009; van de 46Plassche, 2000). Driving mechanisms of sea-level changes include mass changes in land-47based ice, and other processes such as steric expansion and contraction, and dynamic 48oceanographic processes including variations in wind stress and atmospheric pressure 49(Gehrels and Woodworth, 2013).

50Unravelling the relative importance of these processes on multi-decadal to centennial 51timescales requires the development of precise proxy-based sea-level reconstructions that 52extend before the start of instrumental observations, with good age (decadal) and height (sub-53decimetre) control. In the North Atlantic, the most precise reconstructions are developed 54along low-energy coastlines with small tidal ranges where organic-rich salt marshes provide 55environments that are suitable for developing continuous sea-level records over the last few 56millennia (e.g. Gehrels et al., 2005; Kemp et al., 2011).

57Identifying the drivers of regional sea-level change demands multiple observations from 58different parts of any particular ocean basin, which by necessity will be from a variety of 59depositional and tidal range environments (Long et al., 2014). A variety of microfossil types 60that include foraminifera, testate amoebae and diatoms are typically used, on their own or 61occasionally in combination, to constrain palaeomarsh surface elevations and past sea-level 62changes (e.g. Gehrels et al., 2001; Kemp et al., 2009; Charman et al., 2010; Barlow et al., 632013).

64In this paper we develop a new relative sea-level (RSL) reconstruction from a meso-tidal salt 65marsh in western Iceland, an area particularly susceptible to wind-driven sea-level variability

66due to its location in the pathway of low pressure systems. In a previous paper Gehrels et al. 67(2006) reconstructed a 2000-yr record from this site using foraminifera (Fig. 1), and 68identified a single acceleration in sea level that was dated to the beginning of the nineteenth 69century. However, the record was heavily dominated by the upper marsh species *Jadammina* 70macrescens with occasional Paratrochammina (Lepidoparatrochammina) haynesi. This low 71species diversity provided limited constraints on the elevation of the formation of the past 72marsh surface, making it impossible to identify any fluctuations in relative sea-level change 73beyond the 19th century inflection. Here we revisit the study site, Viðarhólmi salt marsh, and 74 focus in on the last five centuries. We exploit the greater sensitivity to elevation (and hence 75sea level) of diatoms to produce a ~500-yr sea-level reconstruction of high vertical precision. 76We also apply new chronological analyses to the upper part of the stratigraphic section 77previously studied to generate an improved age model using new tephra and AMS¹⁴C dates, 78in combination with previous AMS¹⁴C, ¹³⁷Cs and chemostratigraphical analyses. The resulting **79**reconstruction identifies three distinct periods of rapid sea-level rise during the last ~500 80years.

81To assess the potential drivers behind these changes we compare the new record to proxy and 82instrumental reconstructions of the North Atlantic Oscillation (NAO) Index over the same 83 interval. The NAO exerts a strong influence over regional wind patterns, precipitation and 84temperature, mainly in the winter (e.g. Hurrell et al., 2003). The influence of (winter) NAO 85(wNAO) on Atlantic sea level during the instrumental era is well established (Andersson, 862002; Haigh et al., 2010; Kolker and Hameed, 2007; Miller and Douglas, 2007; Tsimplis et 87al., 2005, 2006; Woodworth et al., 2007; Woolf et al., 2003), but its significance in controlling 88dynamic sea-level variability over longer time intervals has not previously been explored. In 89this paper we present proxy evidence of at least two pre-industrial oscillations in sea level 90that broadly correlate to changes in reconstructed wNAO in the North Atlantic Ocean,

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91highlighting the influence of ocean-atmosphere forcing on regional-scale sea-level variability92during past centuries.

932 Study area

94Viðarhólmi salt marsh (64.77°N, 22.42°W) is located on the west coast of Iceland (Fig. 1) in 95an area that has been seismically stable during the late Holocene (Angelier et al., 2004). 96Årnadóttir et al. (2009) estimate modest rates of uplift due to GIA (~1mm/yr) in the period 97AD 1993-2004 based on GPS observations, but Gehrels et al. (2006) documented 1.3 m of 98relative sea-level rise during the last 2000 years, indicating that on millennial time scales this 99coastal area is subsiding. The marsh is underlain by Tertiary basalt (Ward 1971), and 100protected by a barrier spit to the south and by an outcropping Holocene lava flow to the east. 101Several tidal channels dissect the salt marsh. Our fossil sediment section is taken from the 102cleaned face of one of these channels where a 2 m high peat section is exposed (Figs. 1, 2). 103This is the same section where monoliths for the Gehrels et al. (2006) study had been taken in 1042001 and 2003. Today the salt marsh is largely undisturbed by human influence but is 105occasionally grazed by sheep. Dominant plants on the marsh are *Carex lyngbyei, Agrostis* 106*stolonifera, Festuca rubra* and *Puccinellia maritima* (Ingólfsson, 1998). Mean tidal range at 107Viðarhólmi is 2.1 m, mean sea level (MSL) is 0.12 m above the Iceland geodetic datum and 108the highest astronomical tides reach ~2.1 m above MSL (Gehrels et al., 2006).

109Wind patterns in western Iceland are controlled by the position and strength of the Icelandic 110low pressure system which generally results in dominant wind directions from the east, with 111only rare westerlies (Einarsson, 1984). During positive phases of the NAO the Icelandic Low 112tends to deepen and is located further north than during negative phases (Serreze et al., 1997). 113In the 1930s, for example, the average position of the Icelandic low was at 61°N, while the 114shift to a negative NAO mode from the 1940s to the 1970s was associated with a southward 115movement of this low to around 59°N (Angell and Korshover, 1974). In addition, extra-116tropical cyclones tend to track along a more northerly path and are more frequent during a 117positive NAO mode (Carleton, 1988).

1183 Methods

1193.1 Field and laboratory methods

120In September 2009 we cleaned and re-sampled the upper 60 cm of section 3A of Gehrels et 121al. (2006) using monolith tins driven into the cleaned sediment surface. The lithostratigraphy 122of the marsh is detailed in Gehrels et al. (2006) and mainly comprises sandy peat (Fig. 2). 123Sand- and silt-sized material in the section is of volcanic origin and includes tephra. Three 124distinct horizons of silt are visible in the sequence at 54 cm, 34 cm and 14 cm. Section 3A 125contains an orange-brown pumice at 58-60 cm, dated to 1226/7 (Gehrels et al., 2006), which 126we used as the base of the re-sampled section.

127We sampled modern diatoms from four transects across a height range of 0.74 m (35% of the 128tidal range) from just above the Highest Astronomical Tide (HAT) to the coring site in the 129lower part of the mid marsh at an elevation between Mean High Water Springs (MHWS) and 130Mean High Water (MHW) (Fig. 1, Supplementary information Table 1). Surface samples 131were collected with a cylindrical turf cutter. The top 1 cm was sub-sampled in the laboratory 132for diatom analysis. Heights of sample sites were surveyed relative to geodetic and tidal 133datums with a Total Station. Samples for diatom analysis were prepared using the techniques 134detailed in Palmer and Abott (1986). Diatoms were identified using Foged (1974), Hartley et 135al. (1996), Hemphill-Haley (1993), van der Werff and Huls (1957-1974) and classified by the 136halobian classification system (Hustedt, 1953, Hemphill-Haley, 1993).

1373.2 Transfer functions

138We applied a transfer function (Birks et al., 1990) based on present-day microfossil 139assemblages to obtain estimates of palaeomarsh surface elevation from the down-core fossil 140assemblages. Using detrended canonical correspondence analysis (DCCA) in CANOCO 141version 4.5 (ter Braak and Smilauer, 2002) we calculated the length of the environmental 142gradient of the modern diatom dataset at 2.2 standard deviation units. We therefore followed 143the general rule of thumb that, because the DCCA gradient length is greater than 2 standard 144deviation units, sufficient species in the training set have their optima located along the 145environmental gradient and are collectively responding unimodally to elevation across the 146marsh surface (ter Braak and Prentice, 1988). We developed a unimodal weighted averaging 147partial least squared (WA-PLS) model (ter Braak and Juggins, 1993) using the software C² 148(Juggins, 2003). We selected a WA-PLS model with two components ($r^2 = 0.75$, Root Mean **149**Squared Error of Prediction (RMSEP) = 0.09) as this provided a >10% improvement in r_{boot}^2 150and RMSEP compared to a one component model. Adding further components did not 151significantly improve model performance. The observed *versus* predicted marsh surface 152elevations are shown in Fig. 3. The WA-PLS diatom model predicts the elevation of the core 153top to within 1 cm.

154We evaluated the similarity between the modern and fossil assemblages, and therefore the 155robustness of our reconstructions, using the modern analogue technique (MAT) (Overpeck et 156al., 1985; Jackson and Williams, 2004). We considered fossil samples with a minimum 157dissimilarity coefficient (minDC) smaller than the 5th percentile as having a good analogue, 158those with a minDC between the 5th and the 20th percentile as having a close analogue, and 159those with a minDC of more than the 20th percentiles as having a poor modern analogue 160(Simpson, 2007, Watcham et al., 2013). We removed all samples with a poor modern 161analogue from our resulting RSL reconstructions.

1623.3 Chronology

163We added nine high-precision AMS¹⁴C dates (Bronk Ramsey et al., 2007), four bomb-spike 164AMS¹⁴C dates, and a tephra marker to the existing chronological data of Gehrels et al. (2006) 165(Table 1). The chronology of the 2006 record was based on conventional AMS ¹⁴C, ¹³⁷Cs, 166Pb/Li, ²⁰⁶Pb/²⁰⁷Pb and magnetic declination measurements. The new high-precision AMS ¹⁴C 167dates were obtained from fragile, horizontally embedded, detrital plant remains, and the 168exoskeletons of a (non-burrowing) weevil (*Otiorhynchus* sp.). These analyses were conducted 169at the NERC Radiocarbon Facility within the Scottish Universities Environmental Research 170Centre, East Kilbride, Scotland.

171Within the core we detected tephra that erupted in AD 1721 from the Katla volcano located 172ca. 200 km southeast of Viðarhólmi. This is an exceptional find because other historic Katla 173tephras (such as AD 1755) were transported by winds in a northeasterly direction and did not 174reach our field site (Haflidason et al., 2000). The original Gehrels et al. (2006) age model 175suggested that the Katla AD 1721 tephra (Larsen, 2000) could be located in the sampled 176sequence between 34 and 48 cm. We therefore targeted this depth range at 1 cm intervals, 177sieving samples and examining the 25-63 µm fraction under a light microscope. About 60 178tephra shards were picked from each sample, and prepared for electron probe analysis at the 179School of Geosciences, University of Edinburgh. We selected 154 grains on the basis of 180successful preparation and pristineness of the material, and analysed their chemical 181composition on a Cameca SX100 electron microprobe, with rhyolitic (Lipari) and basaltic 182(BCR2g) standards used for calibration (see Hayward, 2012). We identified 39 grains with 183Katla geochemistry (Einarsson et al., 1980; Óladóttir et al., 2008) (Supplementary 184Information Table 2), of which nine had the characteristic K₂O/P₂O₅ signature of historic 185Katla eruptions (Óladóttir et al., 2008). A maximum of five historic Katla grains per sample 186were found at 39 cm; all other samples contained one shard at most. On this basis we

187assigned a date of AD 1721 to the level at 39 cm, assuming that bioturbation and188remobilisation by wind and water subsequently re-distributed some shards over a wider depth189range (e.g. Davies et al., 2007; Gehrels et al., 2008).

190We developed our age-depth model (Fig. 3) using the Bacon package in R (Blaauw and 191Christen, 2011). Bacon requires as input a prior mean accumulation rate which we calculated 192using the depth of the AD 1226-7 pumice tephra at 58 cm (Gehrels et al., 2006; Haflidason et 193al., 1992; Sigurgeirsson 1992). In the 2001, 2003 and 2009 monoliths the pumice tephra was 194found at 58 cm, suggesting negligible sedimentation between sample collection dates. 195Although this does not allow us to reconstruct sea-level changes during the past decade, it 196does enable all analyses to be easily combined into one chronology. The stratigraphy and our 197age-depth model do not show evidence of other significant hiatuses in the record.

1983.4 Sea-level reconstructions

199We translated the palaeo-marsh elevations calculated by the transfer functions into relative 200sea level (RSL) using the equation:

201RSL (m) = sample height (m MSL) - palaeo-marsh elevation (m MSL) (e.g. Gehrels, 1999) 202Results are presented in Table 2. The sample-specific bootstrapped RMSEP gives the vertical 203uncertainty (approximate to 1 σ) for each fossil sample, although in the figures we multiplied 204the errors by 1.96 to 2 σ . All sample ages and errors are based on modelled ages; those from 205dated levels have reduced uncertainties compared to those from intermediate (undated) levels. 206On the basis of four ¹⁴C-dated sea-level index points that directly overlie bedrock, Gehrels et 207al. (2006) concluded that the section is free of any significant compaction. This is in 208agreement with the compaction studies of Brain et al. (2012) who found that thin, 209lithologically homogeneous stratigraphies, like the one described here, are not significantly 210affected by compaction.

211To calculate error envelopes for our sea-level reconstruction we resampled the RSL data 212points in R using their individual age and vertical error estimates. For each of 1,000 213iterations, we sampled random values from the means and (1 standard deviation) errors of the 214age and RSL estimates (assuming normal distributions) and calculated smooth splines 215(smoothing parameter 0.8) through the resampled data points. From the resulting family of 2161,000 smooth splines, we calculated 68% confidence ranges every 5th year between AD 1500 217and 2000. We determined the corresponding rises based on the derivatives of the above 218smooth splines.

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2204 Results

2214.1 Modern diatoms

222The modern diatom flora of Viðarhólmi salt marsh is diverse, but the 28 taxa with an 223abundance of >5% of the total diatom valves counted (TDV) exhibit a strong vertical 224zonation across the marsh (Fig. 5). Assemblages are dominated by the genus *Navicula*, with 225as most abundant species *N. ignota*, *N. cincta type*, and *N. salinarum*. Other abundant species 226are *Luticola mutica* and *Nitzschia filiformis*.

2274.2 Fossil diatoms

228Fossil diatoms (Fig. 6) in the lower part of the core (~45-55 cm) are characterised by 229relatively high percentages (up to 40% TDV) of freshwater species such as *Pinnularia* 230*borealis*. From ~45 cm upward, the fresh- to brackish-water taxon *Navicula cincta* type

231dominates, with a maximum abundance of 71% TDV at 27 cm. In the upper 10 cm, *Luticola* 232*mutica* increases in abundance (max. 34% TDV).

2334.3 Age-depth model

234The age model shows a gradual increase in sedimentation rate from ~0.2 mm/yr at the base of 235the sequence to 3 mm/yr near the top (Fig. 4). The sample-specific age uncertainties vary 236through the section: 95% uncertainty intervals are ~40 years between AD 1570-1650, ~20-30 237years between AD 1775-1895 and ~10-20 years in the periods AD 1650-1775 and AD 1895-2381950. Age uncertainties are smallest (<10 years) from AD 1950 onwards. Age uncertainties of 239our sea-level reconstruction are smaller than those of the individual data points (Fig. 3) due to 240the Bayesian nature of the calculation. The Bayesian algorithms prohibit age-models with 241reversals, so that ages that are highly anomalous do not feature strongly in the final age 242model.

2434.4 Quantitative relative sea-level reconstructions

244We combine the reconstructed marsh surface elevations (Fig. 6) with the age-depth model 245(Fig. 4) to produce a new record of past RSL change (Fig. 7A). Figure 7B shows the amended 246sea-level reconstruction for the past 2000 years, including the older data points of Gehrels et 247al. (2006). The diatom-based transfer function predicts a palaeomarsh surface elevation for 248the new samples with close/good modern analogues of 1.84 to 2.03 m. This falls within the 249range of the palaeomarsh surface elevations independently estimated by the foraminifera 250results in Gehrels et al. (2006). The elevation estimates are primarily controlled by species 251*Navicula ignota, Fragilariforma virescens* and *Opephora marina*. Overall, the reconstruction 252shows a RSL rise of ~0.6 m in the last 500 years. Most of the sea-level rise appears to have 253occurred in three steps, with rapid rise in the 17th century, the late 18th to early 19th century 254and the 20th century.

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2565 Discussion

2575.1 Comparison with other records

258The diatom-based transfer function produces a robust reconstruction that lies within the error 259bars of, and thus is corroborated by, the original foraminifera-based reconstruction from this 260site (Gehrels et al., 2006; Fig. 1C). The high species diversity and species turnover of the 261diatoms, similar to those found by Patterson et al. (2000) in British Columbia, Canada, reveal 262several decadal-scale fluctuations in sea level not resolved in the original foraminifera-based 263reconstruction. Despite samples with poor modern analogues, especially towards the base and 264in the uppermost samples, we can resolve several sea-level fluctuations.

265The pronounced RSL inflection at ~AD 1820 in the foraminifera-based reconstruction for 266Viðarhólmi salt marsh (Gehrels et al., 2006) was largely due to an abrupt change in the 267original age-depth model. Our new age model is smoother and as a result the rapid 268acceleration is removed. The latter part of the record shows a good fit with the Reykjavik 269tide-gauge record (Fig. 7A).

270The overall rise in RSL identified in our new reconstruction (Fig. 7A) of 0.6 m during the last 271~500 years cannot be directly compared with global sea-level reconstructions, such as that of 272Jevrejeva et al. (2006), as the latter is corrected for glacial isostatic adjustment (GIA). We do 273not correct our record for GIA, as the best available data based on Global Positioning System 274(GPS) data amounts to ~1 mm/yr uplift (Árnadóttir et al., 2009), which is not compatible with 275the millennial-scale relative sea-level rise documented in the Viðarhólmi sediments (Gehrels 276et al., 2006). We therefore instead focus on fluctuations in the sea-level record which may 277provide clues for driving mechanisms.

278Interestingly, the proxy RSL reconstructions from the eastern USA (Kemp et al., 2011, 2013), 279Nova Scotia (Gehrels et al., 2005) and north-west Scotland (Barlow et al., 2014) show little 280variability during the past millennium before a late 19th to early 20th century inflection. These 281differences between the Icelandic and other North Atlantic records suggest that regional/local 282influences play a significant role in driving sea-level variability.

2835.2 West Icelandic sea level and NAO

284The multi-decadal variability observed in our new Iceland record is reminiscent of the 285fluctuations observed in the North Atlantic Oscillation (NAO) (e.g. Cornes et al., 2013; 286Hurrell and van Loon, 1997; Jones et al., 1997; and Luterbacher et al., 1999). We therefore 287first explore the relationship between the NAO and sea level in instrumental records, and then 288test the hypothesis that the periods of rapid sea-level rise in our Icelandic salt-marsh proxy 289record are synchronous with reconstructed changes in NAO.

290The influence of the NAO on sea level has been established in different areas such as the 291North Sea area (Wakelin et al., 2003) and the Baltic (Andersson, 2002). The NAO, which is 292defined as the pressure difference between the Azores High and the Icelandic Low, can affect 293Icelandic sea level through air pressure changes and wind stress. Air pressure will influence 294sea level in its vicinity due to the inverted barometer effect which is ~1cm/mbar (Ponte, 2951992; Wunsch and Stammer, 1997); as air pressure rises (falls) so sea level falls (rises). The 296annual average pressure recorded by the Stykkishólmur weather station (~40 km from our 297field site; see Fig. 1) has varied by 12 mbar over the observational period (AD 1949-2012), 298which would translate into sea-level fluctuations of ~12 cm. The NAO, however, is mainly a 299winter phenomenon, and intra-annual variations in average winter (DJF) air pressure are 300considerably larger at 26 mbar. Additionally, the Icelandic Low dominates the wind patterns 301in the vicinity of our field site, and this pressure system is also known to influence sea level 302(e.g. Douglas, 2008; Hong et al., 2000; Kolker and Hameed 2007).

303To evaluate the possible effect of NAO on west Icelandic sea level, we compare (Fig. 8A-D) 304annual mean relative monthly sea level (RMSL) records from Reykjavik, with time-series of 305air pressure, wind speed, and wind direction, averaged across a box encompassing our study 306area (see Fig 9), and the NAO index (<u>http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm</u>). **307**The time-series of air pressure, wind speed and wind direction were derived from MSL **308**pressure and 10 m wind fields, obtained from the 20th century global reanalysis dataset **309**(Compo et al 2011). These meteorological fields are available at a resolution of a data point 310every 6 hours from 1871 to 2011 and have a horizontal resolution of 2°. Data were 311downloaded from the reanalysis web page (<u>http://www.esrl.noaa.gov/psd/data/20thC_Rean/</u>). 312We generated both annual averages and winter (DJF) averages (Fig. 8A-D). To reduce the 313considerable year-to-year variability we applied a 9-year running average (Fig. 8E-H) to the 314derived time-series (which is similar to the resolution of our proxy sea-level record). As **315**expected, there is a negative correlation between (9-year smoothed) air pressure and MSL **316**(annual: r^2 =0.08; winter: r^2 =0.27), which is explained by the inverted barometer effect. There 317is a positive correlation between MSL (9-year smoothed) and wind direction (annual: $r^2=0.01$; **318**winter: r²=0.26). There is a stronger (positive) correlation between MSL (9-year smoothed) **319**and the NAO (annual: $r^2=0.27$; winter: $r^2=0.53$); and wind speed (annual: $r^2=0.54$; winter: **320**r²=0.41).

321To further compare the atmospheric circulation near Iceland with the Reykjavik tide-gauge 322record, we detrend the tide-gauge record (using a linear trend fitted to the complete MSL 323time-series) to remove lower-frequency variability such as that associated with changes in 324ocean volume. We subdivide the tide-gauge data into years in which MSL was >+1sd,

3250<+1sd, 0>-1sd, and <-1sd, and calculate the average atmospheric patterns, over the period 326AD 1871-2011, for these categories (Fig 9).

327As noted above; the Icelandic Low, a persistent centre of low atmospheric pressure off the 328west coast of Iceland, tends to be deeper when sea levels at Reykjavik are higher. The 329dominant wind pattern involves strong winds from both the north and the south, resulting in a 330weak (though still significant) correlation of wind direction with MSL, and a strong 331correlation with wind strength. The combined wind domains generate set-up on the western 332Icelandic coast.

333The instrumental data reveal a strong correlation of NAO-related factors with instrumental 334measurements of sea level. In order to evaluate a potential link between our ~500 year sea-335level record and wNAO we examined several proxy-based reconstructions of wNAO (Glueck 336and Stockton, 2001; Cook et al., 2002; Luterbacher et al., 2002; Trouet et al., 2009). The 337Glueck and Stockton (2001) record is based on data from GISP, and dendrochronological data 338from Finland to represent the northern pole of the NAO, and many tree ring and precipitation 339records from the southern pole. The records by Cook et al. (2002) and Luterbacher et al. 340(2002) are both based on data from a plethora of sites on both sides of the Atlantic. The 341Trouet et al. (2009) record is based on winter precipitation records from Scotland and 342February-to-June drought records from Morocco. There are many reasons why proxy records 343of the NAO may differ (see Trouet et al. (2012) for a review), but we consider the Trouet et 344al. (2009) reconstruction to be most suitable for comparing with the Iceland sea-level record 345due to its north-western European northern pole, and the position of Scotland in the dominant 346wind patterns over the North Atlantic (Fig. 9).

347In Figure 10 we calculate from our sea-level reconstruction (Fig. 10A) rates of sea-level 348change (Fig. 10B) and identify three periods of rapid sea-level rise. We arbitrarily define

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349'rapid' as exceeding the average global sea-level rise during the 20th century (1.7mm/yr, **350**Church and White (2006)). The three periods are: AD 1620-1650, when sea-level rise peaked **351**at ~2 mm/yr, and AD 1780-1850 and AD 1950-2000, when maximum sea-level rise was ~3 352mm/yr. (These figures are based on the most probable interpretation of the data – see section 3533.4.). A comparison with the Trouet et al. (2009) wNAO record (Fig. 10C) shows that the 354three periods in which the rate of sea-level rise is highest are, within age error, synchronous 355with strong shifts toward a more positive wNAO. These shifts are by far the largest within the 356 considered time period. Maximum rates of sea-level rise were achieved towards the end of 357the NAO shifts. The most recent period of rapid sea-level rise (late 20th century) also 358corresponds with strong shifts towards more positive wNAO in the records by Glueck and 359Stockton (2001), Cook et al. (2002), and Luterbacher et al. (2002) (Supplementary Fig. 1). 360Around AD 1800 Luterbacher et al. (2002) also record a marked increase in NAO index 361(Supplementary Fig. 1). The earliest period of rapid sea-level rise does not seem to have a 362corresponding signal in NAO records other than the one by Trouet et al. (2009), but others 363have also found an increased correlation between Atlantic sea level and NAO in more recent 364centuries (e.g. Andersson, 2002).

365From resampling the Trouet et al. (2009) NAO record at the same resolution as a detrended 366version of our RSL record (Supplementary Fig. 1B), which removes longer wavelength 367components of sea level, we calculate a coefficient of 0.3 (p=0.05) for the correlation 368between RSL at Viðarhólmi and the NAO (Fig. 11). This suggests a significant influence of 369NAO on our ~500-year sea level reconstruction, which is the longest record to date on which 370this is demonstrated.

371Our sea-level record shows variability not detected in the record from North Carolina (Kemp372et al., 2011) (Supplementary Fig. 1G). This is to be expected given the regionally specific373forcing mechanisms of North Atlantic sea levels (Long et al., 2014). For example, along the

374Atlantic seaboard of the southeast USA sea levels may be influenced by the strength and
375position of the Gulf Stream (Ezer et al., 2013, Kopp 2013) and easterly winds are dominant.
376Reconstructions of North Atlantic overturning circulation strength (e.g. Wanamaker et al.,
3772012) display little correspondence with our sea-level record.

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3795.3 West Icelandic sea level and other driving mechanisms

380To evaluate the potential of other driving mechanisms we also consider ocean mass changes, 381GIA, and steric sea-level rise as potential drivers of our Icelandic RSL record. Reductions in 382ice volume of the Greenland and Antarctic ice sheets and mountain glaciers produce a non-383uniform sea-level response, with the largest sea-level rise observed in far-field locations 384(Mitrovica et al., 2001). Iceland is located too close to Greenland to be sensitive to any 385potential mass changes of the Greenland Ice Sheet. On the other hand, Iceland is in a far-field 386location with respect to Antarctica, but the lack of correlation with other North Atlantic sea-387level records largely rules out any Antarctic melt signal as a cause of the sea-level variations 388we reconstructed. Although we cannot completely dismiss contributions from mountain 389glaciers, the absence of coherent signals in other sea-level proxy records indicates they would 390have been small or non-existent.

391Our field site is quite far from the major ice fields in Iceland and the magnitude of vertical 392land motion due to changes in ice mass is estimated to be have been small in recent times 393(Árnadóttir et al., 2009) but may have varied in the past. We therefore examined GIA by 394comparing the timing of the periods of rapid sea-level rise with known changes in local ice 395load history in Iceland. Regional data exist from AD 1700 onwards (Supplementary Fig. 1H), 396whereas in the period AD 1400-1700 ice volume changes are largely unconstrained 397(Kirkbride and Dugmore 2008). The ice body most likely to produce crustal loading (and

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398hence RSL rise) in the Viðarhólmi region is Langjökull, but data from other regional ice caps 399and glaciers are reported in Supplementary Fig. 1H for completeness. Of the two major 400glacial advances reported by Flowers et al. (2007), one coincides with rising and the other 401with falling sea level in our reconstruction, showing no coherent response of Viðarhólmi sea 402level to Langjökull mass changes. We therefore reject this as a cause of our reconstructed sea-403level variability. Additionally, there is no obvious correlation between our sea-level 404variability and changes in more distant Icelandic ice masses (Supplementary Fig. 1H), and 405thus no suggestion these provided the forcing mechanism for this variability.

406With regard to thermosteric sea-level rise we hypothesise that reconstructions of sea-surface 407temperature (SST) and sea-floor temperature (SFT) can be used as a proxy for steric sea 408level. We compare our record with two SST records and a SFT from marine core MD99-2275 409(Supplementary Figs. 1I, J), taken from the North Icelandic Shelf (Knudsen et al., 2004; Ran 410et al., 2011; Sicre et al., 2011). Our coastal site and this core site are both dominated by 411Icelandic Coastal Water (Stefánsson and Ólafsson 1991). There is no correspondence between 412the periods of rapid sea-level change and high SST/SFT, suggesting thermosteric effects on 413Viðarhólmi sea level are not significant.

4146 Conclusions

415Only a small number of well-dated late Holocene sea-level reconstructions from the North 416Atlantic are presently available, and these exhibit patterns that reflect a combination of local 417and regional signals (e.g. Long et al., 2014). It is important therefore to increase the spatial 418coverage of well dated sequences and to enhance the resolution of the RSL reconstructions 419where possible.

420This study has improved an existing RSL record from Viðarhólmi salt marsh in western 421Iceland (Gehrels et al., 2006) by adding age control and by developing new quantitative sea-422level reconstructions based on diatoms. Its main conclusions are as follows:

4231) As shown in many other coastal locations, diatoms perform well as a sea-level proxy,424due to their high species diversity, strong elevation control and frequent species turnover.

4252) The careful application of the optimal microfossil group (here, diatoms) can improve 426RSL reconstructions, but such work must proceed in tandem with the construction of precise 427age models. We developed a new age model for Viðarhólmi using a combination of AMS ¹⁴C 428dates, ¹³⁷Cs, geochemical and magnetic markers, as well as a tephra horizons.

4293) We developed new diatom-based RSL reconstructions, using the modern analogue
430technique (MAT), to identify and remove samples that have poor contemporary equivalents.
431After screening our reconstruction shows a ~0.6 m overall (non-GIA corrected) RSL rise
432since AD 1570, and three episodes of rapid RSL when the rate of rise exceeded 1.7 mm/yr:
433AD 1620-1650, AD 1780-1850 and AD 1950-2000.

We hypothesise that Icelandic sea-level variability is controlled by changes in wind 435patterns associated with shifts in NAO phase based on the strong correlation between a 436reconstructed NAO index (Trouet et al., 2009) and our detrended RSL record. This result is 437supported by a positive correlation of the Reykjavik tide-gauge record with regional air 438pressure and wind speed. NAO-related wind patterns generate set-up on the west coast of 439Iceland thereby raising local sea level. Taking into account the potential impact of NAO on 440Icelandic sea level will enhance future predictions of sea-level changes in this region.

4415) The fluctuating nature of the Icelandic RSL record contrasts with other records from442the North Atlantic and highlights the importance of regionally specific driving mechanisms443over centennial timescales.

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711Figure captions

712**Fig. 1.** Location map and previous work. A: Regional map showing location of study site 713(Viðarhólmi) and other locations mentioned in text. B: Aerial photograph of Viðarhólmi salt 714marsh showing location of surface sample transects (T1-4) and sampled section V3A. C: 715Foraminifera-based sea-level reconstruction for Viðarhólmi salt marsh, with 2σ error bars, 716spanning the last 2000 years from Gehrels et al. (2006).

717**Fig. 2**. Stratigraphy and sedimentological data of section V3A, showing dry bulk density 718(DBD), grain-size fractions and lithology (including dated tephras).

719Fig. 3 Transfer function model details. A: Scatter plot of observed *versus* model-predicted
720elevations of modern diatom samples shown in Fig. 5. B: Residuals (predicted minus
721observed sample elevations). RMSEP – root mean squared error of prediction.

722Fig. 4 Age model and output files computed by the software package Bacon (Blaauw and 723Christen, 2011) for section V3A. A: Age-depth model based on ¹⁴C (purple) and other 724(turquoise) dates. The red curve shows the weighted mean ages of all depths, whereas 725greyscales show uncertainties (where darker grey indicates more certain sections). B: Stable 726Markov Chain Monte Carlo run. C: Prior (green curve; gamma distribution with mean 20, 727shape 3) and posterior (grey histogram) distributions for the accumulation rate (yr/cm). D: 728Prior (green curve; beta distribution with strength 3 and mean 0.1) and posterior (grey 729histogram) for the memory. Section sizes were set at 5 mm.

730Fig. 5 The vertical distribution of the main species of diatoms, shown for species greater than
7315% of total valves counted. Diatom classification according to Vos and de Wolf (1993). P
732(blue): Polyhalobian; M (green): Mesohalobian (brackish); O-h (light orange):

733Oligohalobian-halophilous; O-i (dark orange): Oligohalobian-indifferent; H (red): 734Halophobous. MSL - mean sea level.

735Fig. 6 Fossil assemblages of the main species of diatoms used as sea-level proxies. Diatoms
736shown for species greater than 5% of total valves counted. Diatom classification as in Fig. 5.
737Palaeo-marsh surface elevations (PMSE) are also shown. Samples with good/close modern
738analogues are shown as solid circles. Samples with poor modern analogues are shown as
739open circles.

740**Fig.** 7 New relative sea-level reconstruction for western Iceland based on diatoms. A: New 741reconstruction for the last half millennium. Black crosses are data point from levels that were 742directly dated. Grey crosses are data points for which ages are estimated from the age model 743(Fig. 4). Superimposed is the Reykjavik tide-gauge record (www.psmsl.org). B: Composite 744RSL reconstruction for western Iceland, combining the diatom-based reconstruction for the 745last 500 years (this paper) and the foraminifera-based reconstruction for the older part of the 746record (Gehrels et al., 2006).

747**Fig. 8** Annual winter mean time series of air pressure, wind speed, wind direction, and NAO 748index, averaged for the box shown in Fig. 9 over the period 1871-2011. Mean sea level 749(MSL) at Reykjavik is shown as red lines. Upper panels (A-D) show annual data and lower 750panels (E-H) show 9-year running averages. Note that the vertical axes in panels A and E are 751reversed compared to the other panels.

752Fig. 9 Detrended mean sea-level (MSL) recorded at Reykjavik, showing sea levels
753subdivided into four height categories: >1 standard deviation (very high), 0-1 standard
754deviation (high), -1-0 standard deviation (low), and <-1 standard deviation (very low). Maps
755show the average air pressure, wind speed and wind direction for each of the four height
756categories. The box shows the area used to calculate parameters shown in Fig. 8.

Fig. 10 Comparison of our sea-level reconstruction with the NAO proxy record of Trouet et 758al. (2009). A: Sea-level reconstruction for western Iceland. The envelope represents the 68% 759confidence limits calculated from chronological and height errors of data points. B: Rates of 760sea-level change for the Icelandic sea-level reconstruction in panel A. The envelope shows 76168% confidence limits and the line represents the most probably reconstruction. The grey 762vertical bars show the three periods where this line exceeds the 20th century average of 1.7 763mm/yr (Church and White 2006). C: The reconstructed NAO index of Trouet et al. (2009).

Fig. 11 Scatter plot showing the correlation between the detrended sea-level proxy data from 765western Iceland (see Supplementary Figure 1B) and the reconstructed NAO index (Trouet et 766al., 2009).

768Table captions

Table 1 Age-depth data used to reconstruct relative sea-level changes in western Iceland 770during the last 500 years. Sources: 1 - this study; 2 - Gehrels et al. (2006).

771Table 2 Icelandic sea-level data for the last 500 years. I.M. – indicative meaning. MSL –
772mean sea level. Relative sea level (RSL) positions are given relative to present sea level (i.e.
7730 m).















Percentage











