Holocene loess deposition in Iceland: Evidence for millennial-scale atmosphere-ocean coupling in the North Atlantic

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ABSTRACT

We present the first detailed record of Holocene climate variation from Icelandic eolian soil deposits. Seven cold and windy episodes occurred in Iceland during the past 10 k.y., including the well-documented Little Ice Age (0.6–0.1 ka) and the 8.2 ka event. These windy events are associated with enhanced drift-ice discharge into the North Atlantic, and several are associated with evidence for cold and windy climate in central Greenland and diminution of deep-water formation in the North Atlantic. Although the Arctic Oscillation–North Atlantic Oscillation (AO–NAO) has been invoked to explain other climate teleconnections in the North Atlantic, our paleorecord of windiness in Iceland is not consistent with a persistent negative phase of the AO–NAO.

Keywords: Holocene, Iceland, wind transport, grain-size analysis, loess, paleoclimate.

INTRODUCTION

Warmth and stability are usually associated with Holocene climate. Yet several glacial advances (Denton and Karlen, 1973) and pulses of icebergs into the North Atlantic (Bond et al., 1997) occurred during the present interglacial period, the causes of which remain unknown. Iceland is well suited to studying these cooling events because the island is exposed to the rapidly changing North Atlantic climate system, which has a great influence on the Northern Hemisphere. Correlations between the climate records of North Atlantic sediment cores and Greenland ice cores have demonstrated that regionally coherent climate trends in the North Atlantic have characterized the Holocene (Bond et al., 1993, 1997, 2001), and a terrestrial paleoclimate record from Iceland would aid in further constraining the climatic history of the region. However, previous work on Icelandic terrestrial climate proxies, including glacial advances, pollen records, and periods of vegetation and soil formation, has shown little correlation with other climate proxies in the North Atlantic region, particularly those derived from the Greenland ice cores (Gudmundsson, 1997).

Wind can be a sensitive indicator of climate, and the eolian soil-tephra sequences of southern Iceland (Einarsson, 1994) may preserve a record of temporal changes in wind strength. The most complete profile is located near the Hólmsá River on the south coast of Iceland (Thórarinsson, 1967) (Fig. 1). The 6.5-m-thick soil-tephra profile records eolian soil and air-borne tephra deposition during much of the Holocene. We maintain that fluctuations in soil grain size at the profile indicate that cool climate is associated with stronger winds in the North

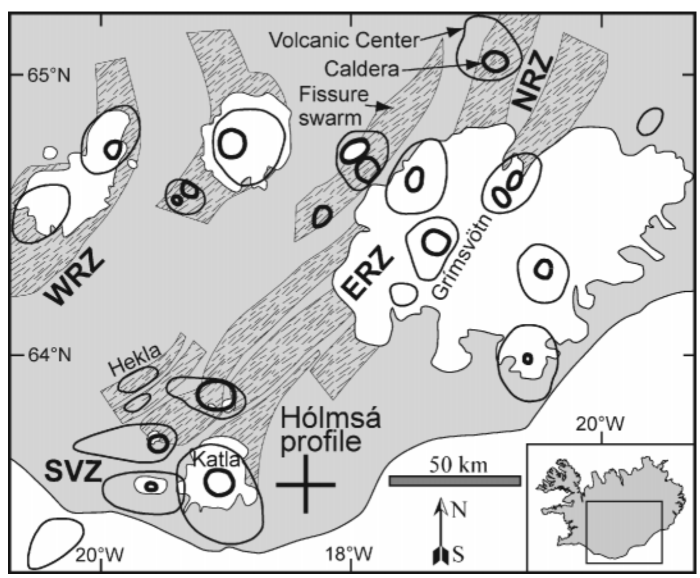

Figure 1. Location of Hólmsá soil profile (cross) is shown in relation to volcanic systems of Iceland. WRZ—Western rift zone; NRZ—Northern rift zone; ERZ—Eastern rift zone; SVZ—Southern volcanic zone. Rift zones are hachured; ice caps are white. Fe-Ti basalts dominate volcanism of Southern volcanic zone and are source of most tephra layers and eolian soil in Hólmsá profile.

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Atlantic. The same winds may be responsible for increased drift-ice transport to more southerly latitudes and enhanced sea salt sodium (Na_{ss}) export to Greenland ice as a result of windier, stormier North Atlantic conditions.

PROFILE DESCRIPTION AND GEOLOGIC SETTING

The profile exhibits distinct alternating bands of soil (54% of total length) and tephra (46% of total), which provide paleoclimate information and marker horizons for dating, respectively (Fig. 2). We identified tephras in the loess section on the basis of their chemistry and appearance, and we assigned calibrated radiocarbon ages that were based on previous work on the profile (Larsen et al., 2001) and on sections from adjacent lakes (Hardardóttir et al., 2001). We are confident in our identification of the tephra marker horizons, and errors in age range from subannual to centennial (Fig. 2). The lack of visible unconformities leads us to believe that the profile is hiatus free and represents continuous deposition.

The soils and tephra in the profile are too coarse (mean grain size, 40–370 μm) to have an off-island provenance. The local provenance of the tephra and soil can be inferred from their chemistry as the volcanic systems of Iceland generate lavas of widely different compositions (Hemond et al., 1993). Tholeiitic mid-ocean ridge basalt dominates the rift zones (which extend across the island from southwest to northeast) and is easily distinguishable from the high Fe-Ti basalts erupted from the volcanic systems of the Southern volcanic zone (Fig. 1). Silicic central volcanoes, including Torfajökull and Hekla, have evolved above many of the long-lived volcanic systems and are the source of several silicic marker horizons in Iceland and elsewhere (Grönvold et al., 1995). Tephra layers of the Hólmsá profile display many different sources of Icelandic explosive volcanism, but basalt with high Fe-Ti compositions erupted from the Southern volcanic zone predominate (Data Repository Fig. DR1; Tables DR1, DR2[1]). Within the Southern volcanic zone, the highly active subglacial Katla volcano is the most likely source of these tephra layers, as it is the closest volcanic center to the profile and has produced numerous phreatomagmatic eruptions of elevated Fe-Ti basalt composition.

The soils between the tephra layers also demonstrate a compositional similarity to the Fe-Ti basalts and tephras unique to the Southern volcanic zone, indicating a similar, proximal, source (Fig. DR1; see footnote 1). The soils in the Hólmsá profile are composed almost entirely of locally derived, reworked, weathered volcanic ash particles from nearby volcanic systems and glacial outflow deposits. Lithic and clay particles are also present in the soil in small quantities.

RESULTS AND DISCUSSION

Wind has played a dominant role in transporting soil to the Hólmsá profile during recent times, and we infer that winds have been primarily responsible for deposition of soil over the entire length of the profile (Einarsson, 1994). Variation of grain size in these soils most likely represents changes in wind strength: weak winds allow deposition of fine particles, whereas stronger winds transport larger particles to the site. Soil availability, including variations in volcanic input, may play a limited role in modifying the grain-size variation in the soil record. However, the soil layers are extremely weathered, suggesting that the soil source was well mixed before being deposited at the profile. This would tend to homogenize grain-size variation in the source, so that large short-term variation in grain size at the soil profile would have to be due to transport processes. Additionally, the grain size and

[1]GSA Data Repository item 2005094, Figures DR1 and DR2 and Tables DR1–DR3, grain-size and geochemical data of soils and geochemical data of tephras, including data of monthly windiness in South Iceland, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

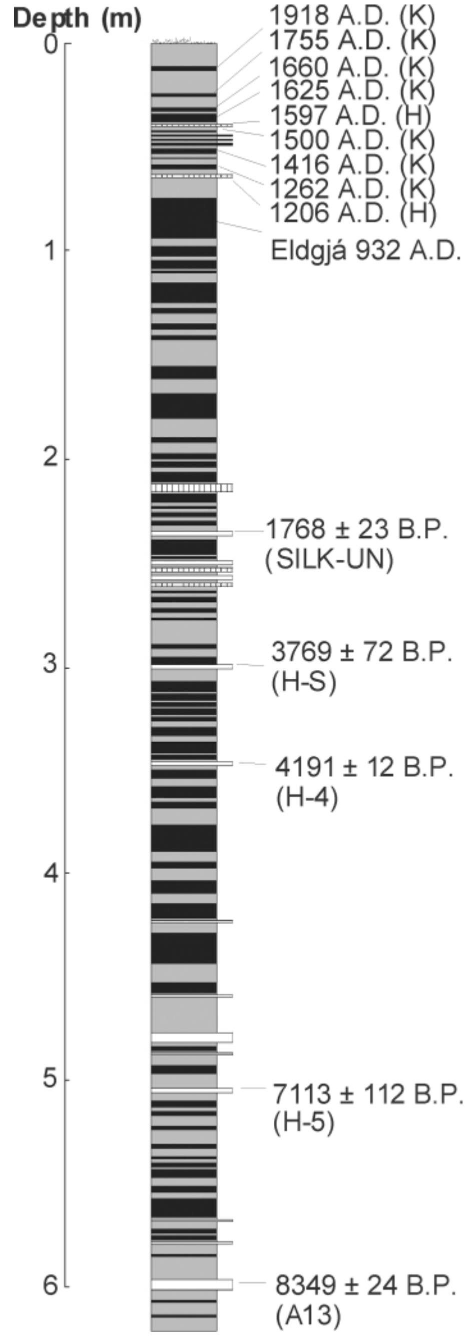

Figure 2. Graphical summary of Hólmsá profile showing tephra and soil stratigraphy, and stratigraphic position of dated marker layers. Soils are gray; Fe-Ti basaltic tephra layers are black. Silicic layers (white) and intermediate tephra layers (vertically hatched) extend out of profile; these layers are from following volcanic centers: K (Katla), H (Hekla), or Torfajökull. Ash layers derived from Grímsvötn are black and extend out of profile. Excluding H-5, dates for all of tephra marker horizons were published together (Larsen et al., 2001); date for H-5 was published separately (Hardardóttir et al., 2001). ^{14}C dates provided for 5 presettlement marker layers are converted to calendar yr B.P. by Calib 4.3 software. Historical eruptions (11) have exact dates. Boundaries between tephra and soil layers are sharp, indicating that age control has not been adversely affected by bioturbation and frost heave.

thickness of the ash layers in the profile exhibit no relationship with the same parameters in the soil layers, suggesting that volcanic input of ash does not control soil grain-size variation in the profile.

Because the source of the soil at Hólmsá is in southern Iceland, we use modern wind data from southern Iceland to understand trends in soil transport and deposition. Wind data were collected at the North Atlantic Treaty Organization (NATO) base in Keflavík, southwest Iceland, from 1949 to 1995 (Keflavík NATO Base Online Weather Database, 2003), and are herein inferred to qualitatively represent annual wind variation in south Iceland (Fig. DR2; footnote 1). Average monthly wind speeds vary little between summer (June–July–August) and winter (December–January–February) months. However, maximum wind speeds recorded during the winter at Keflavík, Iceland, are significantly greater (135–176 km/h) than maximum summer winds speeds (100–107 km/h).

North Atlantic winds are important both on land and at sea because transport of sea ice to the coast of Iceland is aided by strong northerly or northeasterly winds, which are accompanied by cooler ocean-surface temperatures (Bond et al., 1997). This generally occurs during the winter months of particularly cold winters, and the sea ice dissipates with the onset of warm summer air temperatures (Ogilvie, 1992).

The characteristics of long-term climate deterioration are not so different from the modern winter climate conditions around Iceland. Regional winds intensified as the North Atlantic became stormier, cooler, and more ice covered. During the Holocene, several periods defined by more winter-like conditions have been documented in both Greenland Ice Sheet Project 2 (GISP2) ice cores and North Atlantic sediment records, and they appear to be closely linked in time. For example, several episodes of enhanced deposition of Na_{ss} on the Greenland ice sheet have been noted during the Holocene and are thought to be the result of greater storminess and entrainment of sea spray into the atmospheric circulation above Greenland (O'Brien et al., 1995). These atmospheric shifts coincide with periods of cooling (O'Brien et al., 1995) and glacial advance in Scandinavia (Denton and Karlen, 1973), including 0.5 (i.e., the Little Ice Age), 2.8, 5.5, and 8.2 ka.

Additionally, shifts in atmospheric circulation over Greenland are closely linked to the surface hydrography of the North Atlantic (Bond et al., 1993, 1997) (Fig. 3). Increased sea salt concentrations in GISP2 cores correspond to episodes of advection of cold, ice-bearing surface waters (inferred from ice-rafted debris [IRD] in sediment cores) to mid-latitudes (Bond et al., 1997, 2001). Concurrent with several of these cooling events, North Atlantic Deep Water (NADW) formation, inferred from the $\delta^{13}C$ of benthic foraminifers from North Atlantic Ocean Drilling Program Site 980, was reduced (Oppo et al., 2003). The conversion of surface water to deep water provides heat to the atmosphere, such that reduced NADW formation could amplify the effect of an already deteriorating climate regime (Oppo et al., 2003).

Our data suggest that windy periods, indicated by the transport and deposition of coarse sediments in the Hólmsá soil profile, are coeval with cool, stormy periods recorded in GISP2 ice and North Atlantic sediment cores. Coarse soil deposition exhibits distinct variability on millennial time scales, with peaks ca. 8.2, 7.4, 5.5, 4.3, 3.3, 1.6, and 0.6–0.1 ka (Fig. 3). Four grain-size peaks in the soil profile, the Little Ice Age and the 3.3, 5.5, and 8.2 ka events, correspond to documented cooling events observed throughout the North Atlantic (Grove, 1988; Alley et al., 1997; Oppo et al., 2003) and are seen in the following proxies: GISP2 Na_{ss} (O'Brien et al., 1995), IRD records (Bond et al., 2001), benthic $\delta^{13}C$ record (the benthic $\delta^{13}C$ record does not cover the Little Ice Age) (Oppo et al., 2003), and glacial advance in Scandinavia (Denton and Karlen, 1973) (Fig. 3). Intermediate grain-size peaks at 7.4, 4.3, and 1.6 ka do not clearly correspond to cooling events in GISP2 ice or in the benthic $\delta^{13}C$ record, but do have analogous peaks in the IRD stack.

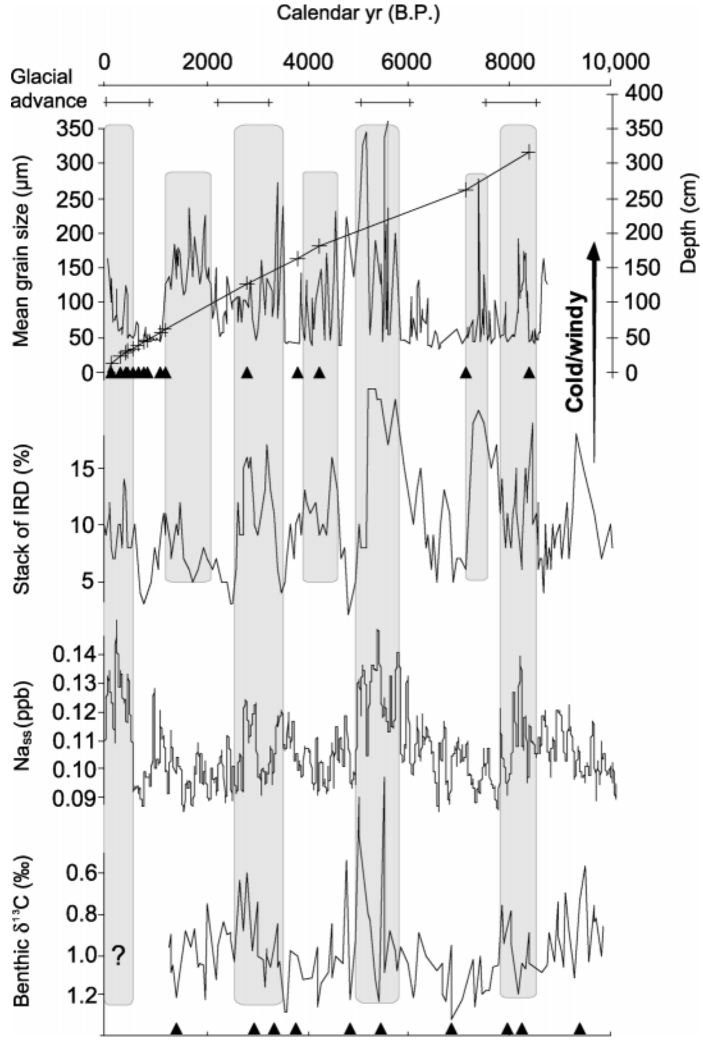

Figure 3. Holocene climate records. Horizontal bars at top of figure indicate glacial advance in Scandinavia (Denton and Karlen, 1973). Top to bottom panels: mean grain size of soils from this study (Table DR3; see footnote 1); stacked record of percentage of hematite-stained grains (i.e., ice-rafted debris [IRD]) (Bond et al., 2001); Greenland Ice Sheet Project 2 sea salt sodium (Na_{ss}) (O'Brien et al., 1995); benthic $\delta^{13}C$ (North Atlantic deep-water contribution) (Oppo et al., 2003). Average interval between our 280 soil samples is ~31 yr between 8.7 and 0 ka. More winterlike conditions increase upward in all panels. Gray bars indicate proposed cooling intervals. Superimposed on top panel are solid triangles and crosses indicating age-dated tephra horizons and near-linear relationship between accumulated soil thickness (tephra layer thickness excluded) and depth (right-side vertical axis). Linear interpolation between tephra marker horizons provides estimated ages for analyzed soils.

The most recent period of cooling, the Little Ice Age, is well constrained in Iceland by written records and human migration (Ogilvie, 1992), and is reflected by a general increase in the baseline of the soil grain-size variation, as well as the magnitude of the grain-size peaks (Fig. 3). This followed a period of warming climate (Medieval Warm Period, 1100–800 yr ago; Björnsson, 1979), when deposition of fine grains occurred.

Winds in Iceland climaxed ca. 5.5 ka; grain sizes in the profile indicate a maximum at this time and show not only the highest mean grain-size values, but also the greatest variability. This mid-Holocene windy event corresponds with the most striking events in the other records, i.e., evidence that NADW formation was reduced to a minimum. GISP2 paleochemical records indicate the most winterlike conditions in the Holocene, and North Atlantic sediment cores indicate intensive incursion of cold, ice-bearing waters from north of Iceland (Fig. 3). Corroborating evidence that NADW formation was reduced to a Holocene minimum during this period is provided in an independent indicator of deep-water variability, $^{231}Pa/^{230}Th$, which also displays a reduction near 5.5 ka (McManus et al., 2004).

The correspondence between the Hólmsá profile's pattern of maxima and independent climate records may indicate a common mechanism linking North Atlantic regional climate signals during the Holocene. One hypothesis is that millennial-scale patterns in North Atlantic cooling reflect preferred modulation of the negative Arctic Oscillation–North Atlantic Oscillation (AO–NAO) phase on millennial time scales (Noren et al., 2002). In our study, Icelandic windiness and Na_{ss} in GISP2 are often observed to be in phase over the length of the Holocene, particularly at the Little Ice Age, the mid-Holocene (5500 yr B.P.), and the 8200 yr B.P. cooling event (Fig. 3). However, the last several decades of observed AO–NAO have revealed an antiphase relationship between Na_{ss} in northern Greenland ice cores (assumed to be similar to GISP2) and windiness in Iceland. During the high AO–NAO phase, Keflavík was four times as likely to experience gusts of wind >92 km/h as during the low AO–NAO phase (Thompson and Wallace, 2001), whereas annually resolved Na concentrations in ice cores from northern Greenland exhibit minima (Fischer, 2001).

Although our loess grain-size data are not consistent with an AO–NAO control on long-term windiness in Iceland, other workers have published paleoclimate records consistent with the AO–NAO mechanism. For example, Keigwin and Pickart (1999), who suggested that the Laurentian Fan sector of the northwest Atlantic actually warmed during the Little Ice Age, noted that their Holocene sea-surface temperature results resemble a pattern associated with the NAO. However, there is conflicting evidence regarding the use of an AO–NAO analog for long-term climate variability in the North Atlantic. Bond et al. (2001) found that during the past 3 k.y., regional cooling patterns in the North Atlantic inferred from the drift-ice cycles have been discordant with modern negative AO–NAO dipole anomaly patterns. Additionally, North Atlantic subpolar, temperate, and subtropical cooling patterns are observed to be roughly in phase during the Holocene, which is not consistent with sea-surface temperature phase offsets that are predicted by a low-phase AO–NAO cooling mechanism (DeMenocal et al., 2000).

Alternatively, our results may be consistent with the hypothesis that North Atlantic cooling patterns resemble reductions in NADW formation, such that the region experiences winterlike conditions (Fig. 3). A similar link is made between the IRD record and reductions in NADW formation (Bond et al., 2001). One problem with this interpretation is that not all of the grain-size maxima in our soil record have corresponding peaks in the benthic $\delta^{13}C$ record from Oppo et al. (2003). However, the IRD record and our loess record exhibit a clear link. The winds that influence these two records may be responding to some other mechanism, and its impact on deep circulation is variable. The mechanism responsible for millennial-scale climate variability remains elusive, but the atmosphere-ocean link that we observe in the Holocene may provide an important clue.

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