Synchronized proxy-based temperature reconstructions reveal mid- to late Holocene climate oscillations in High Arctic Svalbard

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Abstract

Existing paleoclimate data are exceedingly sparse from southern Spitsbergen, a High Arctic region predicted to experience significant environmental changes as a result of amplified warming. We analyzed biotic and isotopic paleolimnological proxies to reconstruct past climate from a lacustrine sediment core, with a basal age of ~5500 years BP, in southern Spitsbergen (77°N). We used fossil Chironomidae assemblages to quantitatively reconstruct past mean July air temperatures and stable oxygen isotope values ($\delta^{18}O$) of these fossils to estimate changes in mean annual air temperature (MAT). These proxy records are strikingly similar and show that the coldest anomaly since the mid-Holocene occurred between 350-50 cal a BP, during the "Little Ice Age", whereas the warmest period in the summer temperature record occurred between 5500-5000 and ~2000 cal a BP. Our findings indicate that the natural long-term air temperature dynamics in our study area are most likely connected to solar minima and positive feedback mechanisms from sea-surface temperature maxima. The results also highlight that the recent temperature increase is unprecedented in its rate with a ~2 °C increase in the summer temperatures during the past ~50 years.

Keywords: Arctic; Chironomidae; Paleoclimate; Spitsbergen; Stable isotopes

Introduction

Arctic regions, such as Svalbard, are highly impacted by present day climate change due to multiple feedback mechanisms related to oceanic, cryospheric and atmospheric processes (Pithan and Mauritsen, 2014). Arctic sea ice extent and volume have been declining (Stroeve *et al.*, 2008; Polyak *et al.*, 2010), and the Arctic Ocean may become seasonally ice-free by the mid-21st century (Wang and Overland, 2009). It was recently demonstrated that the Atlantic Meridional Overturning Circulation (AMOC), which plays a key role in the poleward transport of heat and has a profound impact on climate in northwestern Europe and the High Arctic, may have slowed due to global warming (Landerer *et al.*, 2015). To improve our understanding of the Arctic climate change processes, a long-term perspective of the magnitude and rate of climate fluctuations in the past is necessary.

Arctic lakes and their sedimentary archives provide an opportunity to examine past environmental conditions. Paleolimnological methods, using biotic proxies such as chironomids (Insecta: Diptera), which are sensitive to temperature changes, and stable oxygen isotope signatures (δ^{18}O values) reflecting hydroclimatic conditions, have been found to be very useful in tracking past climate changes (Brooks, 2006; Wooller *et al.*, 2004). Fossil chironomid assemblages have been used to reconstruct temperature during summer, which is their primary season for growth and development (Eggermont and Heiri, 2012), whereas the isotope values of their head capsules can capture the annual δ^{18}O signal of lake water derived from precipitation (Verbruggen *et al.*, 2011). The δ^{18}O of head capsules of chironomid larvae are equilibrated with the δ^{18}O of lakewaters in which they live. In lakes that are not substantially influenced by evaporation or glacial meltwater inputs, the δ^{18}O values of lakewater are controlled by the δ^{18}O value of local precipitation and temperature. In these lakes chironomid δ^{18}O values can subsequently be used to infer mean annual air temperature (MAT) (Wooller *et al.*, 2004).

In Svalbard, quantitative paleoclimatic records are thus far sparse, especially for the southern part of Svalbard, and cover a time span of ≤2000 years (Brooks and Birks, 2004; Isaksson *et al.*, 2005; D'Andrea *et al.*, 2012). There is a pressing need for long-term paleoclimate records from the area for linking climate and AMOC dynamics. In our study area, the North Atlantic Current carries warm surface waters from the Atlantic to high latitudes along the western side of Svalbard. Cold waters from the Arctic Ocean move southwards on the eastern side of Svalbard crossing the warmer waters at the southern tip of Svalbard, where the Polar Front develops (Majewski *et al.*, 2009). Our study area has a significant marine influence from the warm West Spitsbergen Current and the cold Sorrkap Current, and is therefore a climatically and oceanographically sensitive region. For this reason, we examined a lake sediment profile from southern Spitsbergen (Fig. 1) using analyses of chironomid community assemblages to reconstruct mean July air temperature combined with $\delta^{18}O$ values from analyses of chironomid head capsules to infer past MAT. The results of our study are important for understanding the long-term climate processes and land-ocean-atmosphere interactions in this High Arctic climate change hotspot area.

Methods

Study site and sampling

Lake Svartvatnet (76°90’N, 15°66’E, 63 m a.s.l.) is located in a periglacial landscape (Arctic tundra) in southern Spitsbergen, across the Hornsund fjord from the Polish Polar Station (Fig. 1). This thermally stratified lake has a maximum depth of 26.5 m, surface area of ~80 ha and one outlet on its eastern side. Svartvatnet is an oligotrophic lake with a surface water pH of 7.2 (measured June 2013). The lake is annually ice-covered for 9-10 months with an open-season from mid-July to September. At present, the mean July temperature in the area is 4.5 °C, while the MAT is -2.1 °C with annual precipitation remaining below 400 mm (Marsz and Styszyńska, 2013). The lake receives most of its water during the spring/summer as meltwater via a set a shallow creeks, whereas the periglacial soil appears not to produce significant groundwater storage at the study site (Ojala *et al.*, 2016).

A 167-cm sediment core (SV4C) and a parallel 149-cm core (SV4B) were taken from the northern basin of Svartvatnet (Fig. 1) using a light piston corer during the summer of 2013. The sediments consisted of clay gyttja with visible sand and silt/clay laminae (Ojala *et al.*, 2016). The sediment sequences were measured for their physical properties, correlated and the chronology was determined based on a combination of ^{137}Cs, ^{210}Pb, AMS ^{14}C (five dates) and paleomagnetic dating. The dating results and the constructed age-depth model (a Bayesian P-sequence deposition model) (Fig. S1) demonstrated that the SV4C sediment profile covers a 5500-year sedimentary archive with an average accumulation rate of 0.3 mm a^{-1} (Ojala *et al.*, 2016). The accumulation remained otherwise stable and continuous throughout the core but according to the ^{210}Pb dating, the sedimentation rate increased during the 20th century. The well-established sediment chronology, with all the dating results showing good agreement, provides a solid basis for paleoclimatic reconstructions from the Svartvatnet sediment sequence. Detailed descriptions of the lake basin and the sediment, and the associated age-depth model for the Svartvatnet succession was previously published (Ojala *et al.*, 2016).

Analyses

Sediment subsamples (SV4C) for fossil chironomid analysis were prepared using standard methods (Brooks *et al.*, 2007). The wet sediment was sieved through a 100-μm mesh and the residue was examined under a stereomicroscope. Larval head capsules were extracted with fine forceps and mounted permanently on microscope slides. Identification was performed under a light microscope at 400x magnification. The minimum chironomid head capsule number per sample was set to 50

(Heiri and Lotter, 2001). Principal component analysis (PCA) was used to detect primary direction of the chironomid community variance (Abdi and Williams, 2010). The PCA was run with all taxa included using a square-root transformation of the species percentage data. The chironomid-based mean July air temperature reconstruction (CiT) used the trimmed Norwegian weighted-averaging partial least squares (WA-PLS, 3-component) calibration model (Velle *et al.*, 2011). The model has a cross-validated coefficient of determination of 0.86, a root mean squared error of prediction of 0.70 °C and a maximum bias of 0.66 °C. To test whether the reconstruction corresponded to the primary chironomid community variability, the temperatures were compared against the PCA axis 1 scores using Pearson product-moment correlation coefficient and the associated level of statistical significance.

The protocol for $\delta^{18}O$ analysis of chironomid head capsules ($\delta^{18}O_{chir}$) followed Wang *et al.* (2008) without the acid treatment, and was described further by Arppe *et al.* (2017) and Kurki (2016). Approximately 80 µg of cleaned chironomid head capsules were weighed in silver capsules, and measurements of $\delta^{18}O$ values were performed with a Finnigan ThermoQuest TC/EA coupled to a Delta^{Plus}Advantage isotope ratio mass spectrometer at the Laboratory of Chronology, Finnish Museum of Natural History. The $\delta^{18}O$ values are expressed relative to the oxygen isotope ratio of Vienna Standard Mean Ocean Water. The international reference materials IAEA-NO3 (25.6‰), IAEA-601 (23.3‰), ANU sucrose (36.4‰), baleen whale keratin BWBII (14.0‰), and an internally validated IAEA-CH3 cellulose (32.6‰) were used to normalize raw $\delta^{18}O$ values. The reproducibility of similar biogenic reference materials indicates a mean analytical precision (1 σ) of 0.5‰, with a range from 0.4 to 2.5‰ depending on signal (sample) size, which is consistent with the findings of Wang *et al.* (2008). The $\delta^{18}O_{chir}$ values were used to estimate mean annual values of $\delta^{18}O_{lake\ water}$ and MAT following Wooller *et al.* (2004) and Verbruggen *et al.* (2011). The composite errors for the reconstructions, factoring in both measurement uncertainty and calibration error, were calculated according to Pryor *et al.* (2014). They range from 1.4 to 3.6 ‰ (mean 1.6‰) and 1.9 to

4.5 °C (mean = 2.1 °C) for the $\delta^{18}O_{lake\ water}$ and MAT reconstructions, respectively. A more detailed description of the analytical and data processing methods was described by Arppe *et al.* (2017). It should be noted that the $\delta^{18}O_{chir}$ reconstruction of mean annual temperature should be considered tentative owing to reasons discussed below.

Results

Fossil chironomid assemblages of the initial part of the sediment profile (160-90 cm, ~5500-3300 cal a BP) were dominated by *Micropsectra contracta*-type (Fig. 2), which corresponds to morphologically and ecologically similar taxon *M. insignilobus*-type in the chironomid-based calibration set used for the temperature reconstruction (Brooks and Birks, 2000, 2001). This taxon complex is typical for the oligotrophic lakes in Svalbard (Luoto *et al.* 2011; Velle *et al.* 2011). In the mid-part of the profile (90-50 cm, ~3200-1800 cal a BP) the cold-indicating *Hydrobaenus lugubris*-type began to dominate but was later (at ~1800 cal a BP) replaced by another cold prefering taxon *Oliveria*. In the most recent sample representing the present, several warm-water chironomids, such as *Paratanytarsus austriacus*-type and *M. junci*-type, increased that has also been detected in other lakes in Svalbard (Velle *et al.* 2011; Kivilä 2014).

In general, the chironomid PCA axis 1 scores were negative in the lower part of the record but turned into positive scores after ~3500 cal a BP. Reflecting a major shift in chironomid assemblages (decreases in *M. contracta*-type and *Orthocladius trigonolabis*-type and increase in *H. lugubris*-type), chironomid PCA axis 1 scores showed a rapid change at ~3300-3200 cal a BP (~90 cm) and another change of similar magnitude in the most recent samples (decreases in *Oliveridia* and *H. lugubris*-type and increase in *M. junci*-type) (Fig. 2). The chironomid PCA axis 1 scores correlated closely (r=0.91, P<0.001) with the CiT changes during the past 5500 years (Fig. 3). Furthermore, the CiT values were very similar to the $\delta^{18}O_{lake\ water}$ values and the $\delta^{18}O_{chir}$

reconstruction of annual temperatures (Fig. 3). The CiT remained at >5 °C between ~5500-3500 cal a BP with a progressive decline, however, with a short warm period at ~1500 cal a BP and very warm temperatures at the surface sample. The reconstruction of $\delta^{18}O_{\text{lake water}}$ values distinctly mimics the CiT reconstruction but the warmer temperatures between ~5500-3500 cal a BP identified by the CiT are not as well reflected in the isotopic reconstruction. The minimum temperatures were reconstructed for the period between ~300-200 cal a BP with both proxies. In addition to this temperature minimum, simultaneous cold periods were found at ~3400-3200 and 1400-1200 cal a BP.

The surface sediment CiT of 6.6 °C is overestimated compared to the observed long-term mean July air temperature (1978-2014) at the study area of 4.5 °C but close to the temperature measured in June 2016 of 6.0 °C. Therefore, when compared to the present instrumental temperature record, the surface sediment CiT is within the model's prediction error of 0.7 °C. The observed long-term MAT in the area is -4.4 °C being clearly lower than in the $\delta^{18}O$-based reconstruction for the surface sample. However, the reconstructed surface sample MAT of -0.6 °C is closer to the last five-year mean of -1.9 °C, which remains within the reconstruction's sample-specific error estimate of 3.0 °C. When comparing the reconstructed $\delta^{18}O_{\text{lake water}}$ of -9.2 ‰ (sample-specific error 2.4‰) with the observed lake water value of -9.6 ‰, measured from water samples during the summer 2013, the values were found to be very close.

Discussion

Temperature reconstructions and climate variability

According to our previous assessment based on contemporary aquatic communities (Luoto *et al.*, 2016), the most significant confounding factor for chironomid-based temperature reconstructions in the study area (Hornsund) is the potential influence of bird-driven nutrient enrichment. This kind of arctic eutrophication superimposed on the recent climate warming is a typical trend for smaller ponds lying close to shoreline in Svalbard with increasing sizes of arctic-nesting birds in their catchment (Luoto *et al.*, 2014, 2015). However, when comparing the Svartvatnet chironomid stratigraphy (Fig. 2) with the modern dataset (Luoto *et al.*, 2016), the phenomenon of bird-induced eutrophication is not reflected in the chironomid communities of Svartvatnet. Therefore, since our study site is not significantly influenced by birds, it is probable that the long-term biotic record is driven by the direct climate impact. In fact, the PCA results indicated that the chironomid assemblages significantly responded to temperature changes during the past 5500 years, as the chironomid PCA axis 1 scores correlated with the CiT. Furthermore, the $\delta^{18}O_{lake\ water}$ reconstructions showed similar trends with the CiT (Fig. 3) providing evidence that both proxies were reflecting the same environmental variable (temperature), though at different timescales (annual vs. July).

While we consider the $\delta^{18}O_{lake\ water}$ reconstruction a robust representation of past changes in $\delta^{18}O$ values of lake Svartvatnet water and local precipitation, the interpretation of the isotope record in terms of temperature variability is not straightforward. Due to uncertainties in both the present-day and past $\delta^{18}O$/MAT relationships, possible past changes in the locations and pathways of major moisture sources, and the seasonal distribution of precipitation, the $\delta^{18}O_{chir}$-based MAT reconstruction is subject to some uncertainty. The presented MAT reconstruction (Fig. 3) holds true only in a scenario where all the changes observed in $\delta^{18}O_{lake\ water}$ can be attributed to changes in MAT at the site, without associated changes in the abovementioned factors. Indeed, the record of $\delta^{18}O$ values, while carrying a strong temperature dependent signal, is very likely also influenced by other environmental factors such as variations in sea ice extent around Spitsbergen, and should not be considered solely to reflect MAT. A detailed discussion of the $\delta^{18}O$ record was previously presented by Arppe *et al.* (2017).

The reconstructions indicated relatively warm climatic conditions at the beginning of the record, between ~5500 and 3800 cal a BP. This warm period corresponds with the presence of smaller-than-present glaciers in Svalbard (Humlum *et al.*, 2005) and Franz Josef Land (Lubinsky *et al.*, 1999), and with the general timing of the Holocene Climate Optimum (HCO, ~8000-5000 cal a BP) (Wanner *et al.*, 2008). Our results are also in accordance with recent sediment-based Holocene glacier reconstruction from the northwestern coast of the Svalbard Archipelago (Røthe *et al.*, 2015), which shows low inorganic detrital input into the proglacial Kløsa basin, suggesting that influx of meltwater ceased following the possible melting of the Karlbreen glacier. Likewise, Svendsen and Mangerud (1997) concluded that the Linnébreen glacier at the mouth of Isfjorden in Spitsbergen had melted during this period. Based on plant macrofossil analysis, July temperatures may have been up to 1.5 °C warmer compared to the late 20th century in the western coastline of Svalbard (Birks, 1991). Our CiT shows that the summer temperatures between 5500 and 5000 cal a BP in southern Spitsbergen were similar to present day, which is in agreement with most paleoclimate records from Svalbard indicating generally warm mid-Holocene summer conditions (Lubinsky *et al.*, 1999; Humlum *et al.*, 2005; Luoto *et al.*, 2011).

Our CiT record, reflecting summer conditions, shows a general Neoglacial cooling trend from ~5000 cal a BP onwards (Fig 3). Svendsen and Mangerud (1997) suggested that following the HCO, the Linnébreen glacier reoccupied the valley above Linnévatnet between 4600 cal a BP and around 2800 cal a BP, probably in response to a decline in summer insolation and climate cooling. The first one of these episodes is fairly coincidental with two minimum peaks in our CiT. On the other hand, the $\delta^{18}O_{chir}$ record, which incorporates the climatic signal of the cool/cold season, does not show a decline. Summer cooling, from a slightly later peak (4250-4050 cal a BP) than in our record, was recorded by van der Bilt *et al.* (2015) in the Lake Hajeren proglacial sedimentary record (Fig. 3). This may reflect regional differences caused by external forcing mechanisms, or slower response times of small glaciers (van der Bilt *et al.*, 2015).

We document a significant cooling episode in both our proxy records at ~3300 cal a BP, which has previously been detected in the equilibrium-line altitude (ELA) reconstructions from Karlbreen glacier on the northwest coast of Svalbard (Røthe *et al.*, 2015). Although our evidence is mostly based on single data point excursions (Fig. 3), a contemporaneous centennial-scale glacier advance in the Hajaren catchment was also observed by van der Bilt *et al.* (2015), which was linked to orbitally forced summer cooling and increased sea-ice export through the Fram Strait. In addition, a cooling event in our record at 1300 cal a BP is concurrent with the ELA reconstruction (Røthe *et al.*, 2015) and the Linnévatnet record (Svendsen and Mangerud, 1997), suggesting that the glacier response is probably more related to summer air temperature than precipitation changes. Peak erosion due to the presence of a glacier in the Lake Hajaren catchment occurred later, at around 1100 cal a BP (van der Bilt *et al.*, 2015) suggesting that the lack of glacier growth prior to 1100 cal a BP was due to the climate being too dry or too warm in this low-lying catchment.

Typical for lacustrine sites in the Arctic (Miller *et al.*, 2010), the present results do not show clear signs of the Medieval Climate Anomaly (MCA, ~850-1250 CE). The closest study of millennial-scale climate fluctuations to our site was presented by Pawłowska *et al.* (2015), who investigated mass balance and glacial activity in a marine environment at Hornsund fjord. These investigators were not able to identify clear changes in environmental conditions during the MCA as there was a stable and low rate of sediment accumulation and low ice rafted debris flux.

According to our proxies, the general late Holocene cooling trend culminated at ~300-200 cal a BP, coinciding with the end of the Little Ice Age (LIA). The previous ~2000/1000-year paleoclimate reconstructions from Svalbard indicate that the LIA was a rather muted and short-lived event in the area (Velle *et al.*, 2011; D'Andrea et al. 2012) compared to continental Northern Europe, where it lasted for several centuries (Luoto and Nevalainen, 2015, 2016; Zawiska *et al.*, 2017). This is also well reflected in glacier ELA records, since the LIA is well represented in a record from continental Norway (Bakke *et al.*, 2005), while less distinct in the Svalbard glacier record (Røthe *et al.*, 2015), suggesting that short-lived climate events may not be evident in glacier growth. According to our results, the declining trend towards colder LIA conditions may have initiated as early as 700-800 cal a BP, followed by a major cooling shift around 400 cal a BP. This date is in good accordance with the composite of high-resolution proxy climate records from the Arctic by Kaufman *et al.* (2009). It also agrees with the inferred beginning of the LIA at around 1600 CE described by Pawłowska *et al.* (2015) based on the analysis of foraminiferal ancient DNA in the marine environment of Hornsund fjord. Timing of the onset of the LIA at around 700 cal a BP also agrees well with other records from western Svalbard (Svendsen and Mangerud, 1997; van der Bilt *et al.*, 2015) suggesting a regional climate shift.

Our CiT for the surface sample is 3.5 °C higher than the lowest LIA values, whereas the $\delta^{18}O_{chir}$-based reconstruction, if interpreted to solely represent changes in MAT at the site, is >10 °C higher. However, the dramatic negative shift observed in the reconstruction of $\delta^{18}O$ values during the LIA is likely to also reflect the significantly expanded sea ice cover limiting the input of proximally derived moisture, and thus should not be interpreted purely on the basis of MAT. These results nonetheless emphasize the influence of winter months to the annual heat budget in our study area. The annual and summer temperature increase from the LIA to the present appears to have been unprecedentedly rapid over the last 5500 years and clearly reflects the most significant climate shift in the record. As in previous evidence from the circum-Arctic (Kaufman *et al.*, 2009; Luoto *et al.*, 2017), rapid recent warming reverses the general trend of cooling in our reconstructions (Fig. 3). Our CiT record indicates a temperature increase of ~2 °C for the recent decades that is equal to the measured temperature increase during the past 30 years at the Polish Polar Station since 1979 (Marsz and Styszyńska, 2013). The surface sediment CiT of 6.6 °C is higher than the observed long-term mean July air temperature (1978-2014) at the study area of 4.5 °C but close to the present day (2016) temperature of 6.0 °C confirming that the reconstructed values are realistic. Similarly, the $\delta^{18}O_{chir}$ record indicates a MAT value of -0.6 °C for the surface sample that is higher than the

35-year mean of 4.4 °C but closer to the last five-year mean of -1.9 °C. The recently (2013) measured $\delta^{18}O_{lake\ water}$ value (-9.6 ‰) and the inferred $\delta^{18}O_{lake\ water}$ value (-9.2 ‰) are also very close. Hence, the better comparability of the reconstructed values with the more recent observations are most likely owing to the observed rapid temperature increase over the temperature monitoring period (Marsz and Styszyńska, 2013).

External forcing and feedback mechanisms

Decreasing summer solar insolation may have caused the Neoglacial cooling trend in the Arctic region (Wanner *et al.*, 2008). In the North Atlantic region, the Neoglacial cooling is reflected by growing glaciers (Bakke *et al.*, 2010), decreasing sea surface temperatures (SSTs) (Sarnthein *et al.*, 2003; Berner *et al.*, 2010) and ice-core derived temperatures (Lecavalier *et al.*, 2013). In general, North Atlantic surface winds and surface ocean hydrography have been influenced by variations in solar output throughout the Holocene, hence, the surface hydrographic changes may have affected production of North Atlantic Deep Water, potentially providing an additional mechanism for amplifying the solar radiation fluctuations and transmitting them globally (Bond *et al.*, 2001).

The air temperature dynamics in our study appear to be externally forced by solar minima and positive feedback mechanisms related to SST maxima. The cold episodes reconstructed from the current biotic and isotopic records at 3400-3200 and 1400-1200 cal a BP are synchronized with periods of low solar irradiation (Steinhilber *et al.*, 2009; Fig. 3), however, it is likely that combination of several factors triggers the cold and warm episodes. In agreement with Bond *et al.* (2001), our record shows that the LIA is not fully synchronized with the Maunder solar minimum. Cooling during the LIA is significantly connected with atmospheric forcing since a strongly negative NAO index phase prevailed (Trouet *et al.*, 2009; Dylmer *et al.*, 2013; Luoto and Nevalainen, 2017). The warm periods in our summer temperature record, ~5400, ~2200 and ~1600 cal a BP, show correspondence with increases in summer SSTs reconstructed from the northern Norwegian Sea (Sarnthein *et al.*, 2003; Fig. 2). However, these warm phases are not apparent in the isotopic record. Though this might reflect the sensitivity of $\delta^{18}O$ values to precipitation (Langebroek *et al.*, 2011), it more likely mirrors its sensitivity to MAT. The lack of the warm MCA signal in our record is probably due to dominance of Arctic surface water in the western Barents Sea at this time, which contributes to cooler conditions than in continental regions of the Northern Hemisphere (Dylmer *et al.*, 2013).

The recent and most significant temperature increase in our record corresponds to the human-induced increase in greenhouse gases in the atmosphere since the pre-industrial age (Crowley, 2000). Although there is an increase in solar irradiance towards the present (Steinhilber *et al.*, 2009; Fig. 3), it appears to be too small to explain the fast and major increase in the temperatures at our study site. There also exists a possibility of a regional temperature response via ocean-atmosphere heat transport that has been suggested from marine sediments off Western Svalbard (Spielhagen *et al.*, 2011).

Conclusions

Changes in fossil chironomid assemblages and $\delta^{18}O$ values of chironomid head capsules document significant paleoclimate changes during the past ~5500 years in Svalbard. Both proxies showed similar temperature trends, indicating late Holocene cooling and the LIA. The recent temperature increase is unprecedented in its speed and magnitude since the mid Holocene. Although partly associated with single data point excursions, we document connections between periods of cold temperatures and solar radiation minima and warm periods and high SSTs, suggesting that both forcing/feedback mechanisms may play an important role behind the climate dynamics of our study region. The complexity of the regional climate patterns is reinforced by the local glacier influence.

The current record makes a valuable contribution to paleoclimate science, since no previous quantitative estimates of Holocene temperature changes are available from southern Spitsbergen, which is strategically located at the crossing of major warm and cold oceanic currents and where the Polar Front develops. Therefore, knowledge of climate trends and the processes controlling them at our study site provides significant understanding for circum-Arctic and global climate dynamics.

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Figure captions

Figure 1. Map. Lake Svartvatnet (76.895°N, 15.676°E, 63 m a.s.l.) is located 12 km south of the Polish Polar Station on Hornsund fjord, Svalbard.

Figure 2. Chironomid assemblages. Relative abundance of chironomid taxa and the principal component analysis (PCA) axis 1 scores from the Svartvatnet sediment sequence.

Figure 3. Reconstructions. Principal component analysis (PCA) axis 1 scores for fossil chironomid assemblages, chironomid-based mean July air temperature reconstruction (CiT), lake water $\delta^{18}O$ values derived from fossil chironomid head capsules and annual air temperature reconstruction based on the isotope records in Svartvatnet. The $\delta^{18}O$-based reconstruction, represented as anomalies from the record mean, should not be considered directly as a MAT record (discussed by Arppe *et al.* (2017) in more detail). The Svartvatnet data are compared with proxy records of average total solar irradiance (TSI) relative to the solar cycle minimum of the year AD 1986 (Steinhilber *et al.*, 2009), summer sea-surface temperature from northern Norwegian Sea (Sarnthein *et al.*, 2003) and glacier variability in Svalbard (van der Bilt *et al.*, 2015). Cold climate episodes are marked in gray.

Supporting Information Figure S1. Age-depth model originally published in Ojala *et al.* (2016). Dating of the topmost sediments is based on ^{210}Pb and ^{137}Cs (solid black line). Calibrated AMS ^{14}C dates with 95.4% confidence levels (2s) are given in darker gray, black crosses represent their 2s median probability and black dots represent paleosecular variation dates. The age-depth relationship shaded with light gray is based on a Bayesian P-sequence deposition model.