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# Holocene temperature evolution in the Northern Hemisphere high latitudes – Model-data comparisons

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ABSTRACT

Heterogeneous Holocene climate evolutions in the Northern Hemisphere high latitudes are primarily determined by orbital-scale insolation variations and melting ice sheets. Previous inter-model comparisons have revealed that multi-simulation consistencies vary spatially. We, therefore, compared multiple model results with proxy-based reconstructions in Fennoscandia, Greenland, north Canada, Alaska and Siberia.

Our model-data comparisons reveal that data and models generally agree in Fennoscandia, Greenland and Canada, with the early-Holocene warming and subsequent gradual decrease to 0 ka BP (hereinafter referred as ka). In Fennoscandia, simulations and pollen data suggest a 2 °C warming by 8 ka, but this is less expressed in chironomid data. In Canada, a strong early-Holocene warming is suggested by both the simulations and pollen results. In Greenland, the magnitude of early-Holocene warming ranges from 6 °C in simulations to 8 °C in $\delta^{18}O$-based temperatures.

Simulated and reconstructed temperatures are mismatched in Alaska. Pollen data suggest strong early-Holocene warming, while the simulations indicate constant Holocene cooling, and chironomid data show a stable trend. Meanwhile, a high frequency of Alaskan peatland initiation before 9 ka can reflect a either high temperature, high soil moisture or large seasonality. In high-latitude Siberia, although simulations and proxy data depict high Holocene temperatures, these signals are noisy owing to a large spread in the simulations and between pollen and chironomid results. On the whole, the Holocene climate evolutions in most regions (Fennoscandia, Greenland and Canada) are well established and understood, but important questions regarding the Holocene temperature trend and mechanisms remain for Alaska and Siberia.



## 1. Introduction

The Holocene, the most recent geological epoch, experienced detectable climate change. Generally, the Holocene climate evolution can be characterized by an early cool phase followed by substantial warming towards the well-known Holocene Thermal Maximum (HTM) and finally a long-term cooling that ended in the preindustrial era (Marcott et al., 2013; Renssen et al., 2009). The main long-term cooling primarily resulted from solar insolation variations due to changing astronomical parameters (Berger, 1988; Denton et al., 2010; Abe-Ouchi et al., 2013; Buizert et al., 2014). These parameters determine the incoming solar radiation at the top of atmosphere, and lead to latitudinal climate patterns (Berger and Loutre, 1991; Berger, 1978). Retreating ice sheets, including the Laurentide Ice Sheet (LIS) and Fennoscandian Ice Sheet (FIS), add spatial irregularities to this latitudinal pattern, resulting in heterogeneous spatial distributions of simulated temperatures. This spatial heterogeneity was characterized by relatively cool conditions in the early Holocene in some regions, while other areas were relatively warm, as revealed in palaeoclimate modeling studies (Renssen et al., 2009; Blaschek and Renssen, 2013; Zhang et al., 2016). However, the spatio-temporal details of climate during the early Holocene are still uncertain, and inter-model comparisons

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have been conducted to identify consistently simulated climate patterns among independent model results and to detect inconsistent features (Bothe et al., 2013; Eby et al., 2013; Bakker et al., 2014; Zhang et al., submitted). For example, Zhang et al. (submitted) have compared Holocene simulations performed with four different models (LOVECLIM, CCSM3, FAMOUS and HadCM3) and found good multi-model agreements over regions directly influenced by strong ice-sheet cooling, such as in northern Canada, northwest Europe and Greenland. Yet, divergent early-Holocene temperatures across models have been identified in regions where the climate was indirectly affected by the ice sheets, such as Alaska and Siberia.

Even though climate models are useful tools for linking proxy records and understanding the impact of forcings on climate, proxy data are required to validate climate models at an early development stage (Braconnot et al., 2012) and to evaluate the simulations when multiple models perform differently. Climate proxy records are relatively abundant for the Holocene (e.g. Marcott et al., 2013; Sundqvist et al., 2014). To investigate the general patterns of climate evolution, Marcott et al. (2013) for instance have stacked the proxy records over the latitude bands of 30–90°N and 30°S–30°N, and found that the high-latitude cooling trend is opposite to a warming trend in low latitudes during the last 11 kyr. Eldevik et al. (2014) also have compiled climate records on a regional scale to shed light on the climate history of Norway and the Norwegian Sea. Recent progress in proxy-based reconstructions and newly established databases provides ground for a systematical spatio-temporal investigation of Holocene temperature evolutions. For instance, based on the Holocene database of Sundqvist et al. (2014), temperature changes in the north Atlantic region and Fennoscandia (Sejrup et al., 2016), Alaska (Kaufman et al., 2016), the Canadian Arctic and Greenland (Briner et al., 2016) have been recently examined. Although considerable improvements have been achieved in proxy-based reconstructions, proxy data still contain inherent uncertainties. Firstly, climate proxies archive a matrix of environmental variables rather than only a climate signal of interest, as they are influenced by confounding effects (Brooks and Birks, 2001; Birks et al., 2010; Velle et al., 2010). For instance, a summer temperature reconstruction derived from pollen can include a signal related to other variables, such as winter temperature, precipitation, or even non-climatic factors (Seppä et al., 2004; Birks et al., 2010; Li et al., 2015). Moreover, the interpretations of proxy results are primarily based on observed contemporary relationships, implying potential uncertainties in reconstructions as these relationships may change slightly over time (e.g. Jackson et al., 2009). In addition, many processes, such as sediment disturbance and contamination, affect the translation of climate signals to depositional proxy signals, some of which may bring uncertainty into the interpretation of proxy-based results. Consequently, comprehensive comparisons of proxy data with model simulations may shed light on a better climatic interpretation of proxy-based results.

Combining proxy and model results provides opportunities to improve our understanding of climate mechanisms in addition to the interpretation of proxy results and evaluating models. Owing to recent progress in proxy-based reconstructions and model simulations, it is possible to conduct comprehensive model-data comparisons by identifying consistent features and analyzing discrepancies. Indeed, numerous model-data comparisons have been conducted. For instance, model results (in 30–90°N and globally) were recently compared with proxy-based reconstructions to investigate the contradiction of Holocene temperature trends between the reconstructed cooling and the simulated warming, although some of simulations did not include the freshwater forcing (Liu et al., 2014). Another model-data comparison revealed that increasing $CO_2$ precedes global warming during the last deglaciation (Shakun et al., 2012). These model-data comparisons, however, have only used one or two model results to compare with stacked reconstructions and primarily focused on large-scale climate change, such as over 30° latitude bands (i.e. 30–60°N, 60–90°N). The Palaeoclimate Modeling Intercomparison Project (PMIP) also has conducted several model-data comparisons of Holocene climate, but focused mainly on the mid-Holocene (e.g. Masson et al., 1999; Bonfils et al., 2004; Brewer et al., 2007; Zhang et al., 2010; Jiang et al., 2012). Therefore, comparisons between transient multi-model simulations and proxy-based datasets on a detailed sub-continental scale remain unexamined.

In order to evaluate Holocene simulations and to improve our understanding of the transient early-Holocene climate, we compare the four Holocene climate simulations performed with the LOVECLIM, CCSM3, FAMOUS and HadCM3 models that have been discussed by Zhang et al. (submitted), with proxy-based reconstructions of terrestrial temperatures from the Northern Hemisphere high latitudes. In particular, the present study aims to: 1) evaluate model results by identifying consistencies and mismatches between the model results and proxy data over regions on a sub-continental scale; 2) analyze the uncertainty sources of simulations and of quantitative proxy records to illustrate what we can learn about validation of simulations and the interpretation of proxy results; and 3) identify the most probable temperature trends during the Holocene on a sub-continental scale with the aid of additional available evidence.

## 2. Methods

### 2.1. Data & analysis

Proxy data were mainly derived from the Arctic Holocene database of Sundqvist et al. (2014). Sundqvist et al. (2014) collected as many published records as possible, with the selection criteria of: 1) latitude: sites north of 58°N; 2) time-frame: proxy time series extending back at least to 6 ka; 3) temporal resolution: higher than 400 ± 200 yr; and 4) dating frequency: interval in age models smaller than 3000 yr. We picked terrestrial records providing quantitative reconstructions of temperature and conducted a further selection based on the time-frame of the records. As we are interested in climate evolutions of the entire Holocene, the records shorter than 9.5 ka were excluded in order to obtain records that also cover the early Holocene. The exception of this further selection was north Canada where long records are limited by coverage of the LIS before the final melting at ~6.8 ka. In order to obtain a comparable record density in north Canada, all records in the database were collected despite some being shorter than 9.5 kyr. With these extended criteria, 8 pollen records were obtained from the database and used in our analysis, together with additional 4 pollen records from Kerwin et al. (2004). Only one chironomid record was available from north Canada that is not included in our dataset, as we aim to compile multiple records to obtain a regional reconstruction. All together, we selected 61 records from 54 sites that are unevenly distributed over the study area (Fig. 1). High data density is represented in Alaska and Fennoscandia, whereas high-latitude Siberia has a low density. Site information on these proxy records is available from the supplementary information (Table.SI1).

The temperature reconstructions are mainly based on pollen and chironomid assemblages, since these proxy data have been quantitatively interpreted as representing summer temperature, which is our target climatic variable. This proxy-based climate reconstruction conducted by the original authors of individual