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The use of high-resolution gridded climate data in the development of chironomid-based inference models from remote areas

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Abstract The development of chironomid-based air temperature inference models in high latitude regions often relies on limited spatial coverage of meteorological data and/or on punctual measurements of water temperature at the time of sampling. The use of simple linear regression to relate air temperature and latitude was until recently the best method to characterize the air temperature gradient along a latitudinal gradient. However, recent studies have used high-resolution gridded climate data to develop new chironomid-based air temperature inference models. This innovative approach has, however, never been further analyzed to test its reliability. This study presents a method using ArcGIS® to extract air temperatures from a high-resolution global gridded climate data set (New et al. 2002) and to incorporate these new data in a variety of chironomid-based air temperature inference models to test their performance. Results suggest that this method is reliable and produces better estimates of air temperature and will be helpful in the development of further quantitative air temperature inference models in remote areas.

Keywords Gridded climate data · Chironomid · Inference model · Air temperature · Paleoclimatology

Introduction

Recent concerns about the effect of current and future global climate change on arctic and alpine environments have focused efforts on extending our knowledge of past climatic variability in these regions. Paleolimnological sciences have exploited lake-sediment archives to reconstruct quantitatively past variations of a growing number of environmental variables throughout the late Quaternary. Chironomids (Insecta: Diptera: Chironomidae) have been extracted from these sedimentary archives and used for quantitative reconstructions using statistical inference models, which link surface-sediment chironomid assemblages to a suite of physical and chemical variables (Porinchu and MacDonald 2003; Walker

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2001). A close relationship exists between air and surface-water temperatures and chironomid biogeography; however, measuring and monitoring these two variables is problematic in remote areas. The use of summer water temperature in inference models is most common in high-latitude studies, where field sampling is constrained in a short period of time (<10 days) and spatially and economically limited. Summer water temperature is typically measured only once at the time of sampling, and these 'snap-shots' likely do not provide accurate estimates of mean surface-water temperatures. If these 'snap-shot' surface water temperature estimates are used to calibrate midge-based inference models, bias may be introduced in downcore reconstructions. On the other hand, air temperature models in these remote regions are typically based on a sparse network of meteorological stations, and use simple linear regression to relate air temperature to latitude. These air-temperature models may provide reasonable estimates of mean July/August air temperature and/or mean summer temperature, but they do not provide the same spatial or temporal resolution as gridded climate data.

The recent development of high-resolution surface climate data sets offers new tools to estimate climatic variables, which may improve the performance of biologically based inference models. These climate data sets are global in scope and provide Climatic Normal (1961–1990) for remote areas where meteorological station coverage is sparse and does not provide reliable environmental data for statistical analysis. Francis et al. (2006) and Barley et al. (2006) used such gridded high-resolution surface climate data sets (Thompson et al. 1999 and New et al. 2002, respectively) to develop chironomid-based inference models for mean July air temperature, but, to our knowledge, this method has not been rigorously described or tested. In this paper we describe a methodological approach that can be used to extract data from the New et al. (2002) data set, and incorporate these air temperature estimates in a variety of inference models to test their performance.

Extraction of the climate data

High-resolution gridded climate data consist of equidistant grid points which incorporate a series of monthly average values for air temperature and precipitation. In this paper, we used a model presented in New et al. (2002), which used the Climate Normal period from 1961 to 1990, to develop a 10′ latitude/longitude data set of mean monthly surface air temperature. This model is based on publicly available national meteorological data and meteorological data obtained from private sources. These data were subjected to a series of validation steps to test for "internal consistency checks" which ensure their high quality. Model development was based on a spatial interpolation method, also known as a "thin-plate spline surfaces interpolation" (New et al. 2002). Latitude, longitude and elevation of data from each station were taken into account during the model development.

Subsamples of grid points covering the defined study area were extracted from the New et al. (2002) climate data set. These grid points, characterized by longitude (*x*-axis), latitude (*y*-axis) and mean July or August air temperature for the Climate Normal period of 1961–1990 (*z*-axis) were then imported into ArcGIS® to create a grid represented as a surface layer (SL1). The temperature variations along this grid were then represented as a color gradient surface consisting of a defined number of classes, with each class representing a 0.5°C range (Fig. 1). The resulting triangulated irregular network (TIN) layer provided a contour plot which served as a visual tool to test the validity of the climate data set. The co-ordinates of the lakes sampled in the training set and incorporated in the inference models were then added to a second surface layer (SL2). For each lake, a buffer polygon, forming a third surface layer (SL3), was created to select the grid points that were located within the limit of a predetermined radius (8.25 km) from the lake. The radius size was carefully chosen to select at least two and no more than four grid points for each lake. The selected grid points contained by each buffer polygon were then exported as a fourth surface layer (SL4). The "join and relates tool" was then applied on SL3 to link it with SL4 and calculate an average (named to refer to the averaging function in ArcGIS®) July or August air temperature associated with each buffer. These gridded data air temperature estimates were then related to their respective lakes. A high correlation was found between the data derived from the meteorological station Climate Normal period of 1961–1990 and the ones from the closest lakes used in the training set.

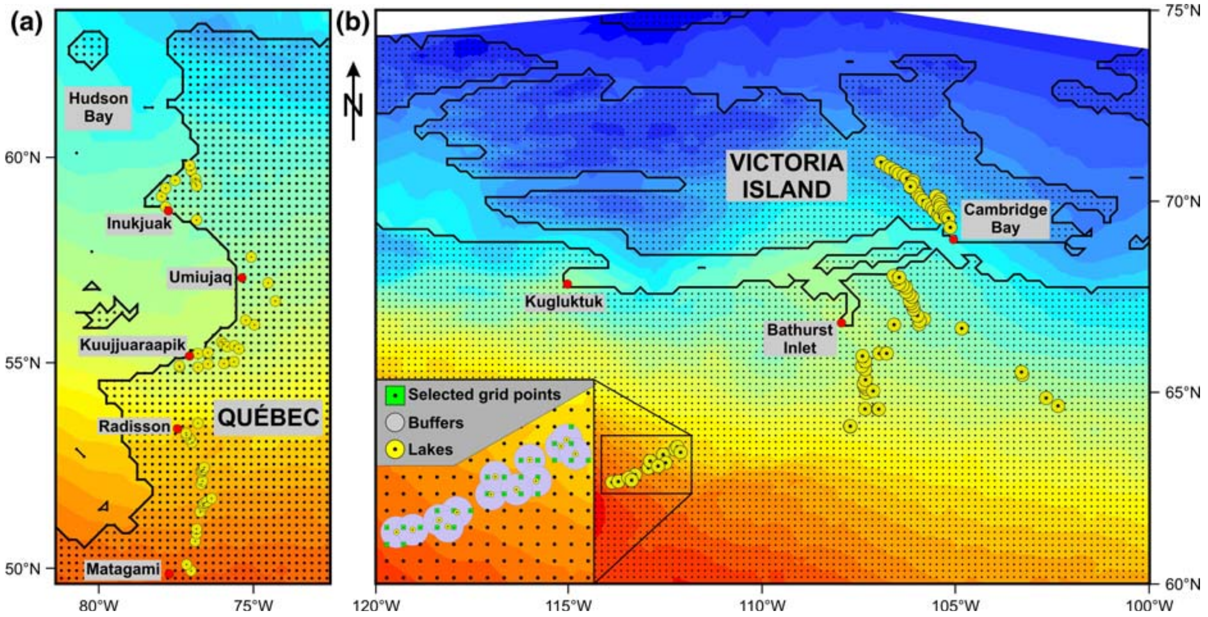

Fig. 1 (**a**) Location of the 52 lakes in northern Québec (Canada) within the climate grid points derived from New et al. (2002). The five meteorological stations previously used in Larocque et al. (2006) are also provided. (**b**) Location of the 90 Central Canadian Arctic lakes used in Porinchu et al. (accepted) within the climate grid points of the region. A schematic of some lakes surrounded by their relative buffer and selected data grid points is also provided

Test and comparison on chironomid-based temperature models

The performance of a recently published 52-lake chironomid-based mean August air temperature inference model [referred as model using station data] from northwestern Québec (Larocque et al. 2006) was re-assessed, making use of the gridded data August air temperature extracted from the New et al. (2002) data set [referred as model using the New et al. (2002) gridded data]. The original mean August air temperature model using station data was developed using a two-component partial least squares (PLS) and produced a midge-based estimate for mean August air temperature with a coefficient of determination (r^2_{jack}) = 0.67; a root mean square error of prediction (RSMEP) = 1.17°C; and a maximum bias = 3.56°C. However, the mean August (1993–1994) air temperature data used in the Larocque et al. (2006) paper were based on a linear interpolation using only five meteorological stations in Québec (Matagami, Radisson, Kuujjuaraapik, Umiujaq and Inukjuak), covering a distance of ~1100 km. The gridded data August air temperature for 1961–1990 was calculated by associating each of the 52 lakes in the training set with a subsample of the 7,168 grid points from the New et al. (2002) model, covering the area between 50–65°N and 65–85°W (Fig. 1a). A new two-component PLS model, based on the original chironomid data set and with the gridded data August air temperature as the predictor environmental variable, was implemented using C2 (Juggins 2003). The performance statistics of the model using the New et al. (2002) gridded data were better with a $r^2_{jack} = 0.71$, a RMSEP = 1.09°C and a maximum bias = 2.58°C. Both the Larocque et al. (2006) model and the model using the New et al. (2002) gridded data were applied downcore to a northern Southampton Island lake described in Rolland et al. (2008) (Fig. 2). The resulting chironomid-based inferred temperatures indicate that the new model using the New et al. (2002) gridded data systematically decreases the air temperature inferences by ~1.3°C, which is significantly different from the air temperature inferences derived from the Larocque et al. (2006) model (*t*-test p value < 0.0001).

The method described in this paper was also applied to a new training set from the central Canadian Arctic (Porinchu et al. accepted) for which

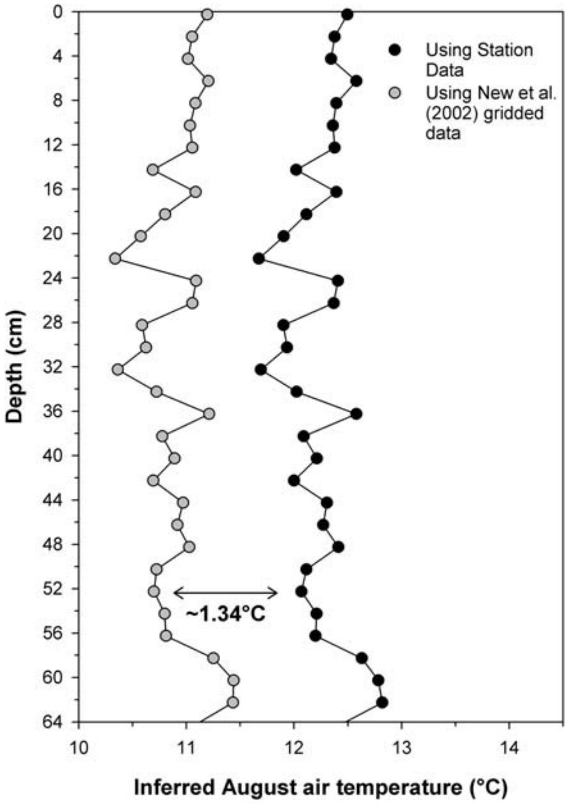

Fig. 2 Chironomid-based August air temperature (°C) reconstructions in a northern Southampton Island lake (Nunavut, Canada) using both August air temperature calculated using station data (temperature against latitude model; Larocque et al. 2006), and August air temperature derived from high-resolution climate data (New et al. 2002)

surface water temperature was initially the sole climate variable modeled. In the Porinchu et al. (accepted) paper, simple linear regression relating air temperature to latitude was not feasible, as only three meteorological stations existed in the region covered by the training set, which spanned a 1,500-km latitudinal gradient. As described above, the training set lakes in the central Canadian Arctic calibration set were associated with a subsample of the 8,633 grid points covering the area in the gridded data set between 60–75°N and 100–120°W, and the average July air temperature was calculated for each lake (Fig. 1b). These data were then used in the regression and calibration analyses. The resulting model provides the first chironomid-based July air temperature model ($r^2_{jack} = 0.77$, RMSEP = 1.03°C and maximum bias of 1.37°C) for this study region. The results of the July air temperature model using the New et al. (2002) gridded data compare favorably with the chironomid-based surface water temperature inference model ($r^2_{jack} = 0.75$, RMSEP = 1.39°C and maximum bias of 2.33°C; Porinchu et al. accepted).

Discussion and conclusions

This study provided new insights into the use of high-resolution gridded climate data for the development of inference models applied in Arctic chironomid-based paleoclimatic studies. The results presented here suggest that this method is reliable and can be applied rapidly to previously published training sets and may help to improve model performance.

In this study, high-resolution gridded climate data were applied to regions with relatively limited relief. We believe that the use of a 10′-resolution model in mountainous environments, i.e. western North America or the eastern Canadian Arctic, where relief and associated environmental variables strongly influence air temperature, may not be reliable.

The newly developed August air temperature model using the New et al. (2002) gridded data for northwestern Québec has slightly better performance than the original one published in Larocque et al. (2006). The most interesting and important change relates to the maximum bias value, which is approximately 1°C lower in the new model. The original model was based on mean August air temperatures calculated for the period 1993–1994, i.e. 2 years prior to the year of surface sediment sampling. The 2-year mean August air temperature in the original model may not have represented accurately the natural climate conditions at each lake, especially compared to the 30-year Climate Normal (1961–1990), and may be the explanation why the maximum bias in the original model was so high.

It is important to note that the magnitude and rates of climate change observed in this region in the post-1990 period may bias the chironomid-based air temperature models that are calibrated against the 1961–1990 Climate Normal, by systematically underestimating the temperature optimum and tolerance of each taxon. If sediment samples have been collected post-1995, it is important that they are calibrated against the most recent Climate Normal period (1971–2000). The mean August air temperatures incorporated in the Larocque et al. (2006) study were

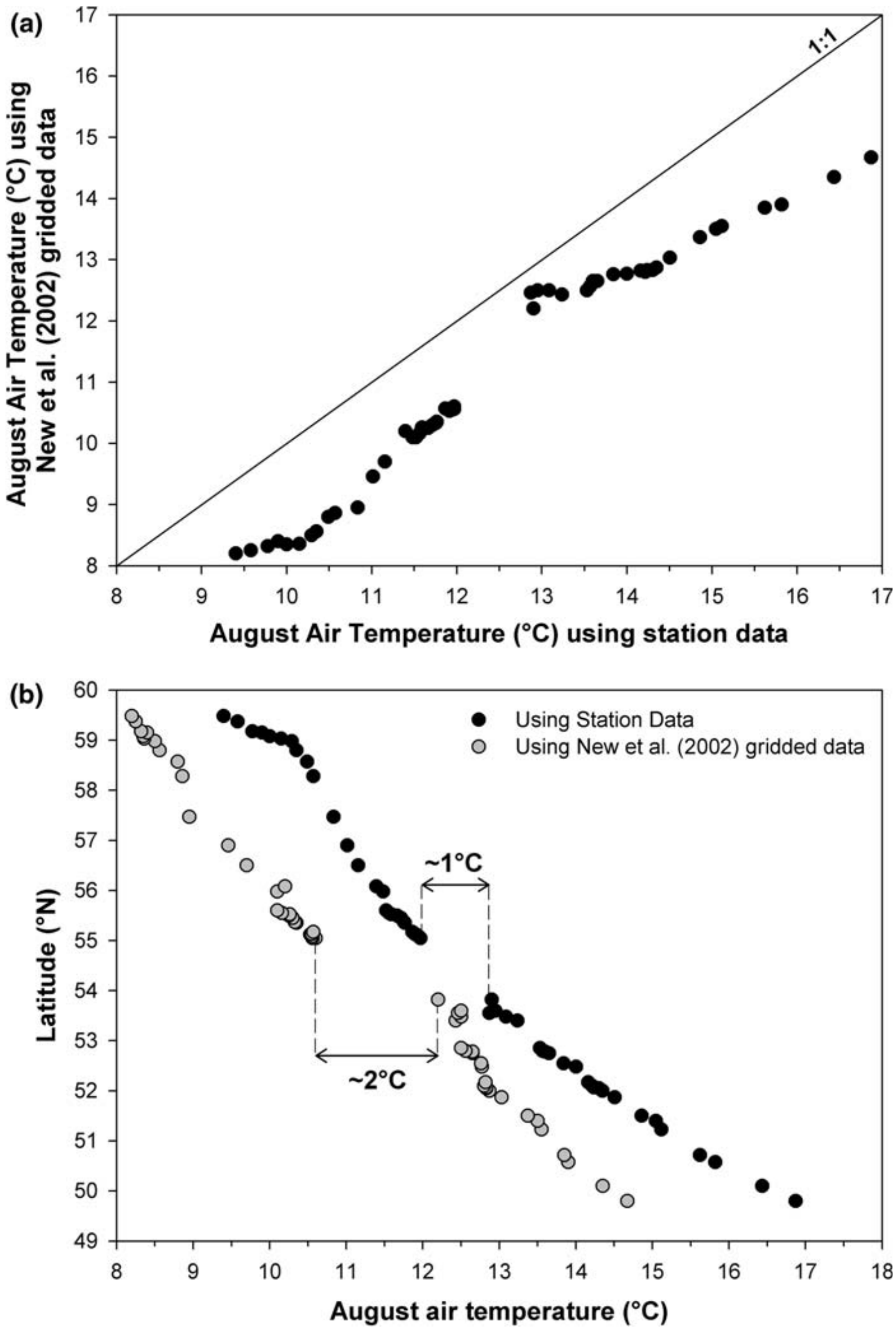

Fig. 3 (**a**) Relationship between the August air temperature derived from meteorological station data (calculated using a linear regression of air temperature and latitude) and the August air temperature derived from high-resolution climate data (New et al. 2002). (**b**) Relationship between average/mean August air temperature and latitude

on average 1.38 ± 0.37°C higher than those calculated with the 1961–1990 Climate Normal data set (Fig. 3a). As demonstrated, the air temperature model, which was based on 1961–1990 Climate Normal, did not modify the trend in air temperature reconstructions when it was applied to sedimented midge assemblages, but it did systematically decrease inferred temperature values (Fig. 2). However, it is important to note that this new temperature reconstruction is not more representative of the climatic conditions on Southampton Island, with the inferred temperature in the surface sample (11.2°C) being greater than the August air temperature of the Island (~8.0°C; 1995–2004; Environment Canada 2002).

The original model, published in Larocque et al. (2006) did not include any high arctic lakes, and overestimated the temperature reconstruction. Nevertheless, the colder temperature reconstructions obtained with the new model suggest that this decrease may be of significance if one is attempting to provide quantitative and absolute estimates of paleotemperatures associated with specific events, i.e. medieval climate optima, Little Ice Age, 8.2 k year event, or if such reconstructions are being incorporated in regional and temporal paleoclimate syntheses. This bias might be corrected by comparing the 1961–1990 Climatic Normal to the recent 1990–2007 climate values. The resulting correction factor, i.e. magnitude of warming that has occurred for the specific study region, could then be applied systematically down-core or applied to each average air temperature value prior model development. However, it is important to keep in mind that high arctic lakes are usually characterized by low sedimentation rates and low concentrations of chironomid head capsules, which may sometimes require the use of more than the top 0.5–1.0 cm of surface sediment for model development. In these situations, where the surface sediments integrate a greater duration of time, it may be more appropriate to use the 1961–1990 Climate Normal.

The method presented in this paper also revealed potential problems in using air temperature estimates based on simple linear regression of air temperature and latitude. In the original model (Larocque et al. 2006), surface sediment samples were not recovered between 54 and 55°N, creating a 1°C temperature gap in this portion of the training set. However, the revised August air temperature model using the New et al. (2002) gridded data revealed that a 2°C gap existed in the same latitudinal range (Fig. 3b). This suggests that air temperature estimates based on simple linear regression and a limited meteorological station network do not capture spatial variations in the study area as well as the gridded model and therefore will bias chironomid temperature optima and tolerances. It appears that the gridded model can resolve variations in the temperature gradient, i.e. the distance between mapped isotherms is variable in the gridded data set (Fig. 1a).

Despite some limitations in using this method, which requires some basic familiarity with ArcGIS® and its spatial analyses tools, the use of such high-resolution gridded climate data offers a new tool to expand previous and future inference models that are developed in remote and poorly monitored regions.

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