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Paleo-climate of the central European uplands during the last glacial maximum based on glacier mass-balance modeling

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ABSTRACT

During the last glacial maximum (LGM), glaciers existed in scattered mountainous locations in central Europe between the major ice masses of Fennoscandia and the Alps. A positive degree-day glacier mass-balance model is used to constrain paleo-climate conditions associated with reconstructed LGM glacier extents of four central European upland regions: the Vosges Mountains, the Black Forest, the Bavarian Forest, and the Giant Mountains. With reduced precipitation (25–75%), reflecting a drier LGM climate, the modeling yields temperature depressions of 8–15°C. To reproduce past glaciers more severe cooling is required in the west than in the east, indicating a strong west–east temperature anomaly gradient.

Introduction

During the Quaternary period, major climate fluctuations caused expansion and decay of continental-scale ice sheets and mountain glaciers (Ehlers and Gibbard, 2007). During the last glacial maximum (LGM) about 18–21 ka, northern Europe was covered by the Fennoscandian ice sheet, and there were ice caps and extensive valley glaciers in the European Alps. In between these extensive ice masses, several Central European upland regions had minor valley and cirque glaciers that have been constrained by radiocarbon, luminescence, and exposure dating (Raab and Völkel, 2003; Mercier and Jeser, 2004; Carr et al., 2007). Although the extent of past glaciation is fairly well known for the central European uplands, the LGM paleo-climate that provided a favorable environment for snow accumulation and glacier growth in this region is not well documented.

The European LGM paleo-climate has previously been investigated using both proxy data and modeling techniques (e.g., Peyron et al., 1998; Strandberg et al., 2011). Pollen records from non-glaciated regions of Europe have been used to reconstruct LGM climate (Peyron et al., 1998; Tarasov et al., 1999). For regions north of the Pyrenees and the Alps, Peyron et al. (1998) derived a mean annual temperature 12 ± 3°C cooler than today, and a mean annual precipitation 60 ± 20% lower than today. Reduced LGM precipitation is also supported by Florineth and Schlüchter (2000), who argue that a southward shift of the polar front caused a drier climate. A glacier mass-balance model using the glacial geological record of past mountain glaciers was presented by Allen et al. (2008a), which suggests temperature depressions between 12.0°C and 17.3°C for regions north and south of the European Alps (Allen et al., 2008b). The LGM cooling inferred from climate modeling has generally been less severe than the LGM cooling inferred from pollen data (Kageyama et al., 2001; Jost et al., 2005; Kageyama et al., 2006; Ramstein et al., 2007; Strandberg et al., 2011). Strandberg et al. (2011) used a regional climate model to derive annual average temperatures 5–10°C cooler than present-day climate for the ice-free areas in central Europe during the LGM. Both the pollen data and climate models have also indicated that there was a longitudinal temperature anomaly gradient, with more intense cooling towards the west (Peyron et al., 1998; Kageyama et al., 2006).

The formerly glaciated regions of the central European uplands offer an excellent opportunity for investigating terrestrial climate during past glaciation. Because glaciers are highly sensitive to climate shifts, variations in past glacier extent can be used to quantify paleo-climate. Here we use a degree-day glacier mass-balance model in conjunction with the glacial geological record to reconstruct the LGM paleo-climate for four central European mountain regions.

Study area

The study area includes four mountain regions in the LGM ice-free corridor between the Fennoscandian ice sheet and the ice masses of the Alps (Fig. 1): the Vosges Mountains, the Black Forest, the Bavarian Forest, and the Giant Mountains. These mid-latitude uplands are located between 48°N and 51°N, and between 7°E (Vosges) and 16°E (Giant Mountains). Their highest summits reach altitudes of 1400–1600 m asl. Each of the four mountain regions experienced Pleistocene glaciation that has been documented by mapping and dating glacial

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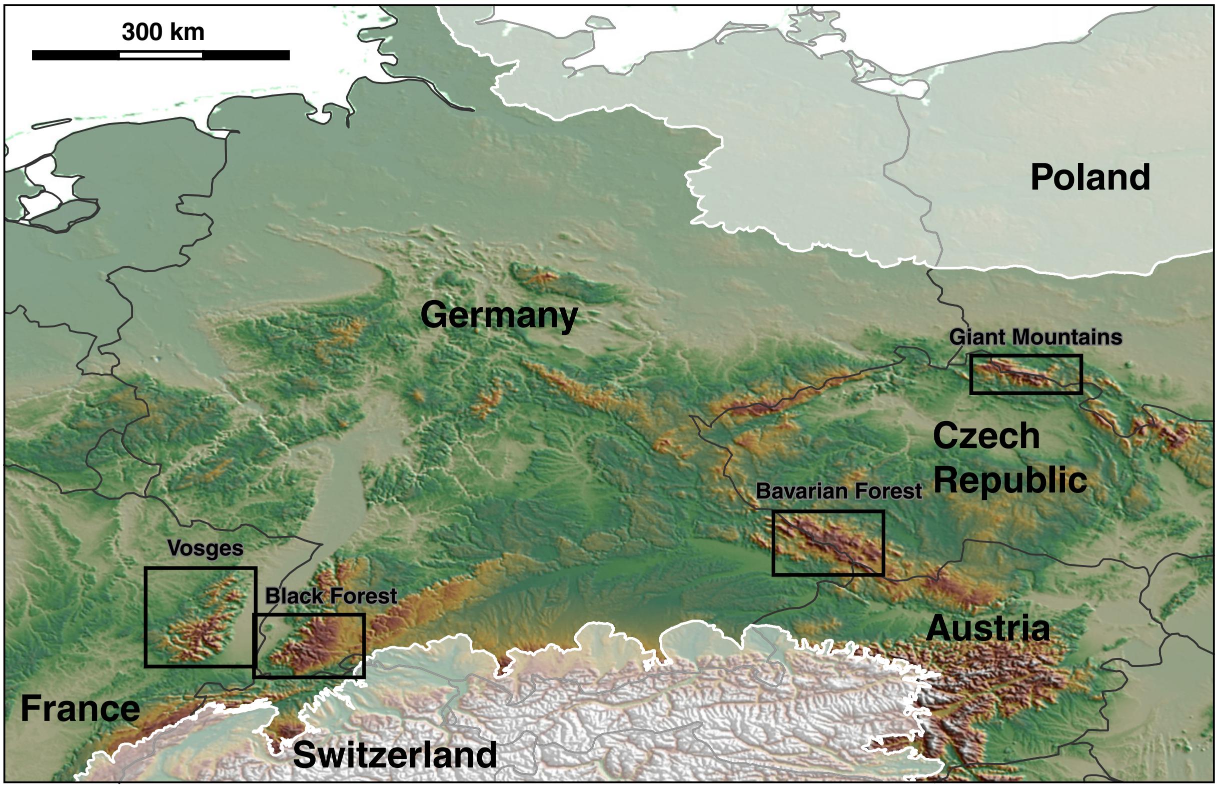

Figure 1. Map of Central Europe with marked model domains. The four study regions are located in between the LGM Fennoscandian ice sheet and the Alps' glaciation as shown by white shading (LGM ice cover according to Ehlers and Gibbard, 2004).

deposits (Partsch, 1894; Ergenzinger, 1967; Ehlers and Gibbard, 2004). For the Vosges Mountains (NE France), Mercier and Jeser (2004) used moraines with ^{10}Be exposure ages (Mercier et al., 1999) to reconstruct an ice cap with associated outlet glaciers that extended up to 15–40 km in length during the LGM. For the Black Forest Mountains (SW Germany; ca. 80 km east of the Vosges Mountains), Fiebig et al. (2004) argued for an LGM ice cap, with glaciers up to ca. 20 km long. For the Bavarian Forest (SE Germany), accumulation-areas in the summit regions above 1300 m asl fed valley glaciers up to ca. 7 km long (Ergenzinger, 1967; Hauner, 1980; Raab and Völkel, 2003; Fiebig et al., 2004) that have been identified as LGM in age based on luminescence dating (Raab and Völkel, 2003). For the Giant Mountains (N Czech Republic), mapping and ^{10}Be exposure ages (Mercier et al., 2000; Engel et al., 2011) indicate that LGM glaciers were 3 to 10 km long (Partsch, 1894; Chmal and Traczyk, 1999; Carr et al., 2002, 2007). Generally, during the LGM, glaciation extent in the central European uplands decreased from west to east.

Methods

For each of the four mountain regions, we used previous glacial reconstructions (Partsch, 1894; Ergenzinger, 1967; Ehlers and Gibbard, 2004) as targets for glacier simulations designed to constrain paleoclimate changes necessary to explain the extent and pattern of LGM glaciation (Fig. 2). We estimated the glacier mass balance (MB, mm/year) using a positive degree-day (PDD) approach (Laumann and Reeh, 1993; Braithwaite, 1995, 2008):

$$MB = \sum P_{snow} - \sum T^{+} \times DDF \quad (1)$$

where P_{snow} is the mean monthly precipitation (mm) for months with a mean monthly temperature below a snowfall threshold of +1°C, T^{+} is the number of monthly positive degree-days (°C*days), and DDF is the degree-day factor (mm/°C/day) for melting. To reflect different melting conditions we ran multiple simulations with DDF values of 2.5, 4.1, and 8.0 mm/°C/day. We used the DDF of 4.1 mm/°C/day as a preferred DDF based on the DDF compilation presented by Braithwaite (2008). As present-day climate we used the interpolated high resolution (30 s, ca. 1 km) mean monthly temperature and precipitation from the WorldClim dataset (Hijmans et al., 2005; version 1.4) based on available weather station data and the 90-m Shuttle Radar Topography Mission elevation. To reconstruct the paleo-climate we ran the model with stepwise climate perturbations until there was a match between the modeled and the reconstructed accumulation-areas (positive mass balance), assuming an accumulation-area ratio of 65% (Meierding, 1982; Kern and László, 2010). We ran the model with stepwise (25% steps) precipitation perturbations from −75% to +50%, assuming an LGM seasonal pattern of precipitation similar to today, and stepwise temperature perturbations of 0.1°C for all months.

Testing the PDD approach

As a test of the PDD approach we ran the model for two regions with present-day glaciers included in the GLIMS database (Raup et al., 2007) in the Swiss Alps and the Norwegian mountains (Fig. 3). While the Norwegian mountain model yields an accumulation-area of 65% for present-day glaciers with a DDF of 3.1 mm/°C/day, the Swiss Alps model yields a larger accumulation-area with DDF values of 2.5–8.0 mm/°C/day. The large modeled accumulation-area for the Swiss Alps, compared to observations, might partly be explained by the recent rapid retreat of glaciers in the Alps (Paul et al., 2004). In an additional experiment, we examined the temperature perturbations necessary to give a 65% accumulation-area ratio with a DDF of 4.1 mm/°C/day. Temperature perturbations ranged from −0.8°C (Norwegian mountains) to +1.3°C (Swiss Alps), indicating the level of model sensitivity to climate. In summary, moderate adjustments

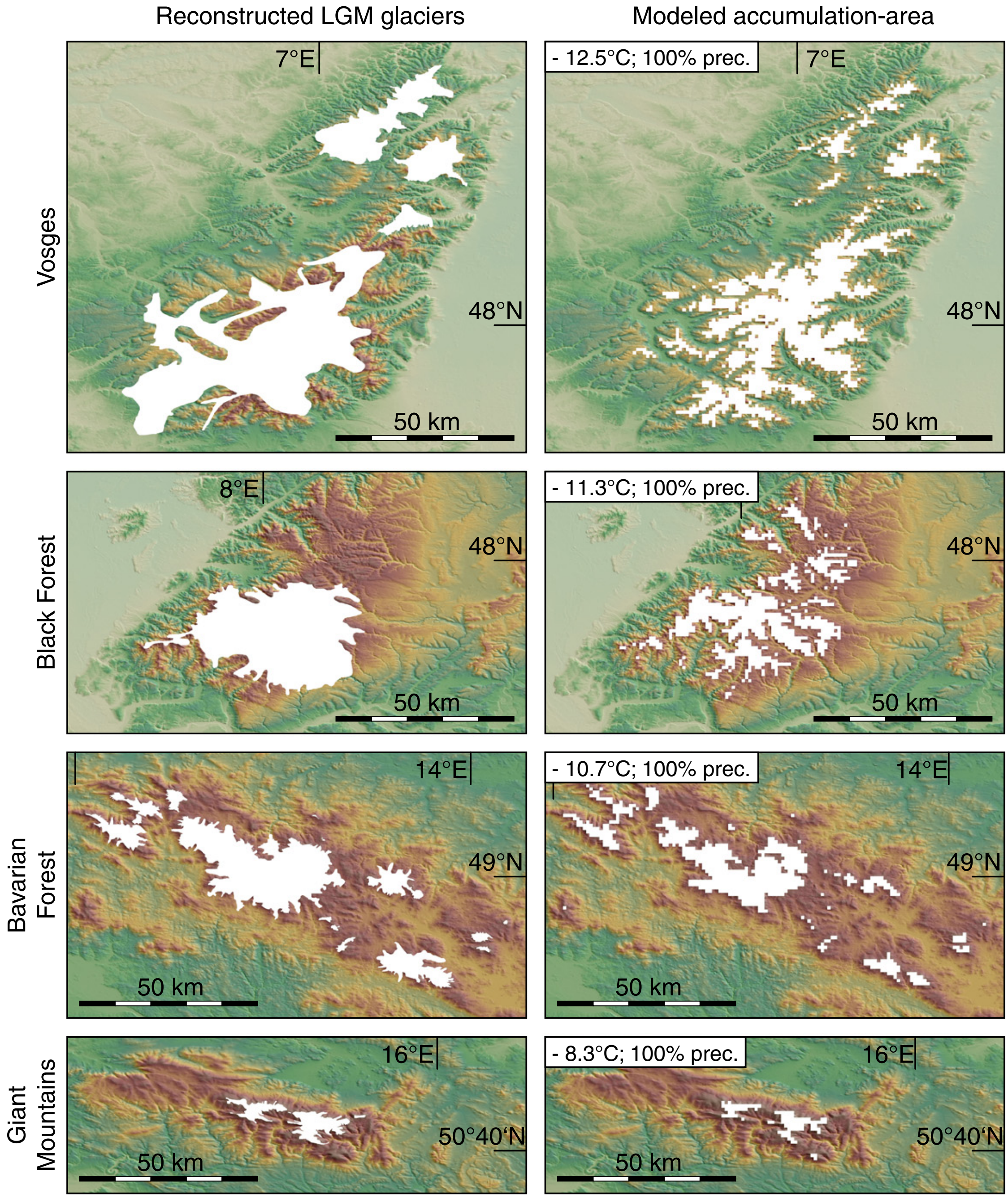

Figure 2. Reconstructed LGM glaciers and modeled accumulation-area (white) of the four domains. The reconstructions are from Ehlers and Gibbard (2004) for the Vosges and the Black Forest, from Ergenzinger (1967) for the Bavarian Forest, and from Partsch (1894) for the Giant Mountains. For the modeled accumulation-areas, equal climate perturbations (upper left corner of the maps) were applied for all months.

are required to reproduce present-day glacier accumulation-areas and good spatial conformity (Fig. 3) lends credibility to the method as a tool for coarse-grained climate analysis.

To test the model sensitivity of accumulation-area ratio differences we performed the modeling with accumulation-area ratio targets of 50% in addition to 65%. The difference in temperature perturbations between an accumulation-area ratio target of 65% and 50% ranges from 0.2°C to 0.5°C for the full set of model runs of the four model domains. These minor temperature perturbation differences indicate that the exact accumulation-area ratio target is not of crucial importance for general paleo-climate approximations.

Results

Climate perturbations required to reproduce the reconstructed LGM accumulation-areas are presented in Figure 4, with modeled accumulation-area examples shown in Figure 2. The cooling required to reproduce the LGM accumulation-areas, using precipitation perturbations ranging from +50% to −75% and equal temperature (°C) and precipitation (%) perturbations for all months, decreases from southwest to northeast, with values of 10.7–14.8°C (Vosges Mountains), 9.1–13.7°C (Black Forest), 8.7–12.7°C (Bavarian Forest), and 6.7–10.3°C (Giant Mountains). The difference in modeled

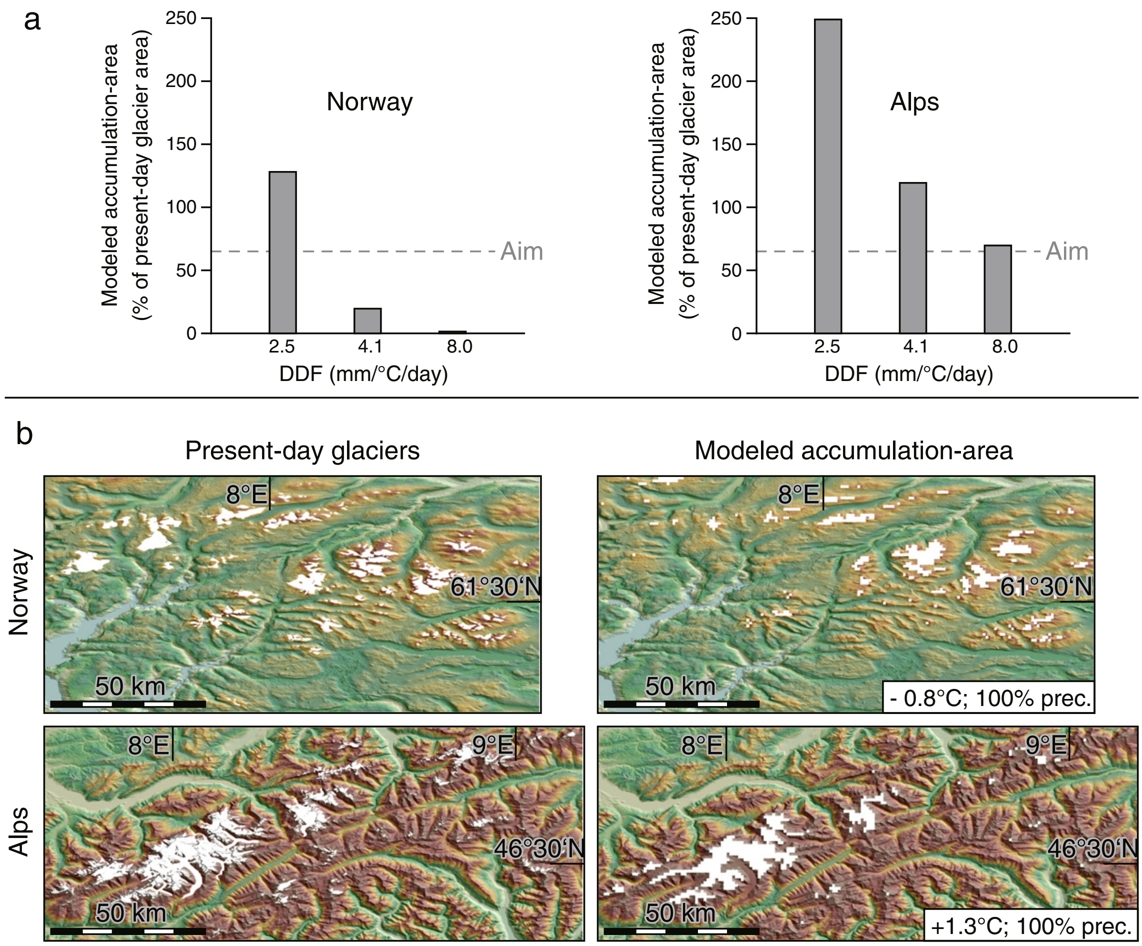

Figure 3. a) Modeled accumulation-area as ratio of present-day glacier area for DDF values of 2.5, 4.1, and 8.0 mm/°C/day, as a test of the mass-balance modeling approach. b) Present-day glaciers from the GLIMS database (Raup et al., 2007) and modeled accumulation-area (white) with a DDF of 4.1 mm/°C/day and temperature perturbations. For the modeled accumulation-areas, equal climate perturbations (upper left corner of the maps) were applied for all months.

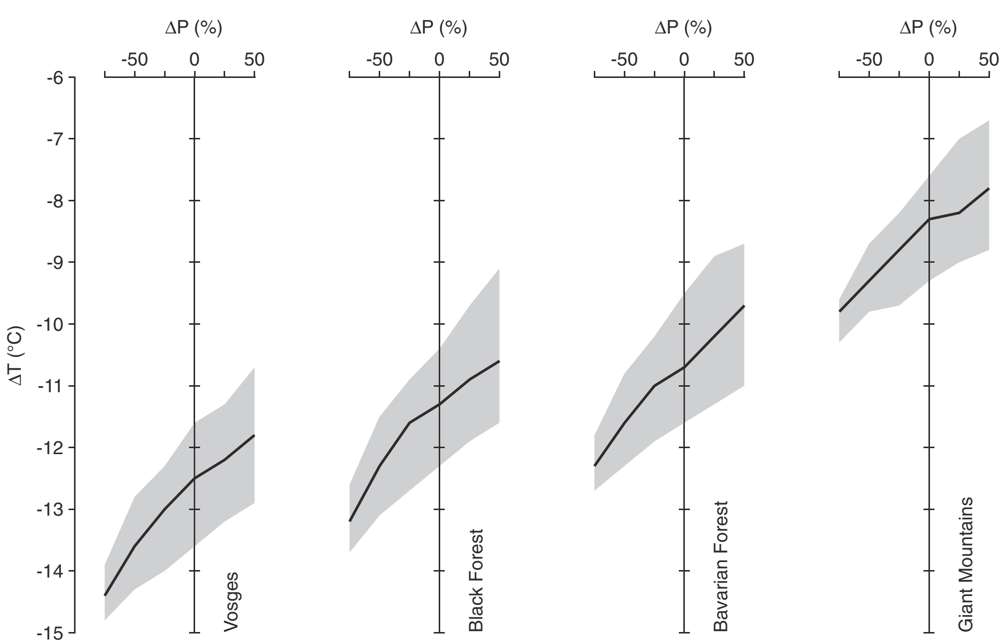

Figure 4. Climate perturbations (equally applied to all months) required to reproduce reconstructed LGM accumulation-areas (Fig. 2) for the four central Europe model domains. The black lines represent models with a DDF of 4.1 mm/°C/day, and the gray areas represent models with a DDF ranging from 2.5 mm/°C/day to 8.0 mm/°C/day.

cooling between using a DDF value of 2.5 mm/°C/day and 8.0 mm/°C/day is 0.7–2.5°C.

Discussion

Our paleo-climate results generally fit well with previous reconstructions of the central European LGM climate. The LGM climate in central Europe was most likely significantly drier than today (Peyron et al., 1998; Florineth and Schlüchter, 2000; Jost et al., 2005; Strandberg et al., 2011), implying that the models with precipitation reduction should yield more accurate LGM cooling. Assuming that the LGM precipitation was 25–75% lower than today, the cooling required to reproduce LGM accumulation-areas is 8–15°C. This matches well with the reconstructed temperature depression of 12 ± 3°C based on pollen records (Peyron et al., 1998), although different LGM lapse rates may complicate comparison of high and low altitude proxies (Wright, 1961; Strandberg et al., 2011). Atmospheric models have commonly yielded slightly less cooling for LGM climate than other reconstruction methods (Kageyama et al., 2001; Jost et al., 2005; Kageyama et al., 2006; Ramstein et al., 2007; Strandberg et al., 2011). However, comparing the glacier mass-balance model outcome for the Vosges Mountains and the Bavarian Forest (Southern Germany) with the altitude adjusted LGM temperatures of Strandberg et al. (2011: Table 3), the models yield similar temperatures. For the Vosges Mountains and the Black Forest, our modeled LGM cooling is slightly lower than the LGM cooling reported by Allen et al. (2008b), at 13.9–17.2°C and 12.0–15.3°C, respectively, based on another PDD mass-balance model. The difference can be attributed to different modeling approaches (Allen et al., 2008a) or varying input data for present-day climate. Although there is a slight difference in LGM cooling between the two mass-balance models, both support the assumption of a strong longitudinal temperature gradient with less cooling in the Carpathian Mountains.

There are several sources of potential error in the paleo-climate modeling approach used here. These include inaccuracies in the DDF value, the accumulation-area ratio, the reconstructed glacier extent, or the present-day climate. The temperature perturbations of -0.8°C and $+1.3$°C necessary to yield a 65% accumulation-area for the Norway and Alps regions (Fig. 3) indicate the potential temperature uncertainty of a few degrees C. In addition, we have assumed equal LGM cooling throughout the year and LGM seasonal distribution of the precipitation similar to today, and these assumptions might not capture actual LGM conditions with more severe winter cooling (Strandberg et al., 2011). While rising positive temperatures will always increase the melting, decreased temperatures below the snowfall threshold of $+1$°C will not affect the snow accumulation. As a result, the model temperature perturbations will more likely reflect perturbations in summer temperatures rather than winter temperatures. In summary, our glacier mass-balance paleo-climate reconstruction has uncertainty associated with necessary assumptions and data, with an estimated cumulative temperature uncertainty of at least 2°C, and thus the LGM climate results (Fig. 4) should be interpreted with care.

For central Europe north of the Alps, limited climate proxy data for the LGM has previously been presented (Peyron et al., 1998; Allen et al., 2008b). Our reconstructed LGM climate for four mountain regions can therefore add important data against which to test atmospheric models (Strandberg et al., 2011). An important characteristic of our reconstructions is a strong temperature anomaly gradient from west to east, with an average temperature depression that is 4.2°C cooler in the Vosges Mountains than in the Giant Mountains. This agrees well with the findings of Peyron et al. (1998) and Kageyama et al. (2006), based on pollen data and climate modeling, as well as the PDD modeling of Allen et al. (2008b). This east–west gradient may relate large-scale atmospheric circulation shifts induced by the large ice masses or the LGM southern sea ice boundary (Kageyama et al., 2006).

Conclusions

We have used a positive degree-day glacier mass-balance approach to model the LGM paleo-climate for four mountain regions in central Europe. Assuming a decreased LGM precipitation of 25–75%, we arrive at an LGM cooling of 8–15°C. The modeling indicates less severe cooling moving eastward from the Vosges Mountains in the southwest to the Black Forest, the Bavarian Forest, and the Giant Mountains. These results are consistent with proxy data and illustrate a strong LGM temperature anomaly gradient from west to east that may relate to large-scale atmospheric circulation shifts and the LGM southern sea ice boundary.

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