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Sensitivity of the Late Saalian (140 kyrs BP) and LGM (21 kyrs BP) Eurasian ice sheet surface mass balance to vegetation feedbacks

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[1] This work uses an atmospheric general circulation model (AGCM) asynchronously coupled to an equilibrium vegetation model to investigate whether vegetation feedbacks could be one of the reasons why the Late Saalian ice sheet (140 kyrs BP) in Eurasia was substantially larger than the Last Glacial Maximum (LGM, 21 kyrs BP) Eurasian ice sheet. The modeled vegetation changes induce a regional cooling for the Late Saalian while they cause a slight regional warming for LGM. As a result, ablation along the margins of the Late Saalian ice sheet is significantly reduced, leading to an increased surface mass balance, while there are no significant mass balance changes observed from vegetation feedbacks at LGM.

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1. Introduction

[2] Numerous studies have shown that vegetation influences the regional and global climate through changes in albedo and modifications to the hydrological cycle [*Charney*, 1975; *Kleidon et al.*, 2000; *Brovkin et al.*, 2003]. At high latitudes, a strong feedback is caused by the higher albedo of tundra-type vegetation compared to boreal forest, in particular when a snow cover is present. The transition from taiga to tundra at a given place thus induces a regional cooling. Similarly, *Crowley and Baum* [1997] reported that glacial vegetation with its reduced forest extent over the boreal regions caused a regional cooling of 2°C to 4°C in western Europe and Siberia in LGM atmospheric general circulation model (AGCM) simulations [*Kubatzki and Claussen*, 1998; *Levis et al.*, 1999; *Crucifix and Hewitt*, 2005]. It is worth noting that the strongest impacts of LGM vegetation were found in studies using the present-day potential vegetation in LGM control runs. The present-day vegetation distribution is more similar to LGM biogeography because agricultural surfaces are more similar to steppes than forests.

[3] Here we focus on the sensitivity of the Late Saalian (140 kyrs BP) Eurasian ice sheet to different prescribed and modeled vegetation distributions. The West Eurasian ice sheet was significantly larger during the Late Saalian than the ice sheet in this region during LGM [*Svendsen et al.*, 2004]. We address the question of whether vegetation feedbacks on the Late Saalian ice sheet's surface mass balance contributed to this difference. We use the LMDZ4 atmospheric general circulation model [*Hourdin et al.*, 2006] asynchronously coupled with the BIOME4 vegetation model [*Kaplan et al.*, 2003]. Similar experiments are carried out for the LGM allowing a comparison between the results. The impacts of other environmental factors on regional climate, such as dust deposition on snow and proglacial lakes during the Late Saalian, the Early Weichselian and LGM investigated by *Colleoni et al.* [2009] and *Krinner et al.* [2004, 2006].

2. Methods

[4] The LMDZ4 atmospheric general circulation model [*Hourdin et al.*, 2006] and the BIOME4 equilibrium vegetation model [*Kaplan et al.*, 2003] were asynchronously coupled. Since no vegetation map is compiled for the Late Saalian, the LGM and Late Saalian climates were initially obtained by forcing the LMDZ4 model with the existing LGM vegetation map by *Crowley* [1995] (runs C21 and C140, Figure 1). New vegetation maps were subsequently computed by forcing BIOME4 with the monthly mean and minimum daily temperatures, the monthly mean precipitation and the cloud cover fraction obtained from the two previous C21 and C140 AGCM simulations. Steady state was obtained after three iterations. The final AGCM runs, using LGM and Saalian vegetation maps shown in Figures 1b and 1c, are referred to as B21 for the LGM and B140 for the Late Saalian.

[5] All AGCM simulations are 21 years long. The first year is discarded in the analyses as spinup. All simulations take into account the effect of proglacial lakes and dust deposition on snow. Since we prescribed the initial LGM vegetation, the simulations are considered as control runs. The surface mass balance is calculated after the temperature-index method of *Ohmura et al.* [1996]. Simulations were forced using LGM sea surface temperatures from *Paul and Schäfer-Neth* [2003]. Boundary conditions are set using the modelled LGM dust deposition rates from *Mahowald et al.* [1999], orbital parameters from *Berger and Loutre* [1991] and greenhouse gases from *Petit et al.* [2001] and *Spahni et al.* [2005]. Late Saalian ice topography is obtained from *Peyaud* [2006] while LGM is modeled using ICE-5G [*Peltier*, 2004]. The equations and details on the Late Saalian boundary conditions are given in the auxiliary material and discussed by *Colleoni et al.* [2009].[1]

3. Results

3.1. LGM and Late Saalian Vegetation Maps

[6] The annual maximum foliage projected cover (see auxiliary material) used for simulations C21 (and C140) is

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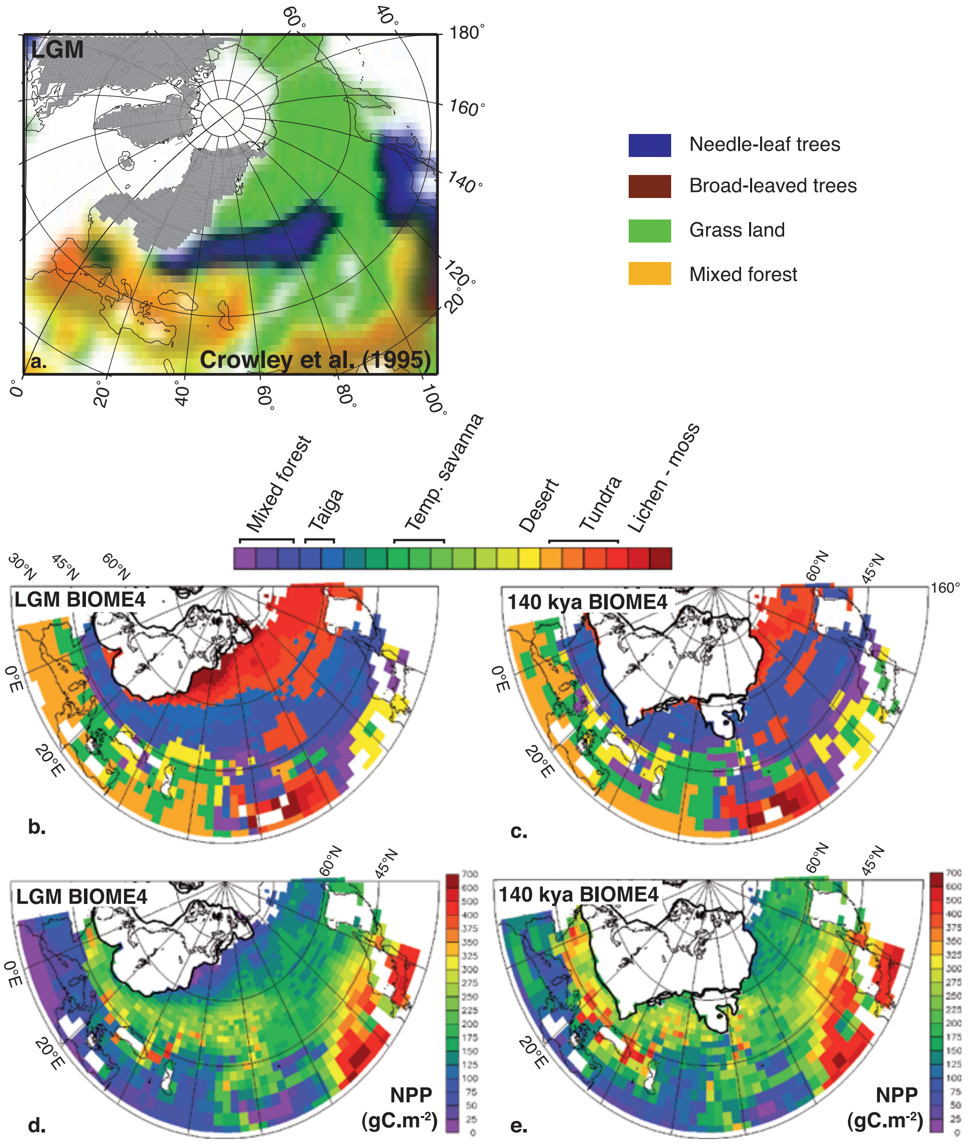

Figure 1. Annual foliage projected cover (dimensionless, see auxiliary material) for: (a) C21 and C140 using the paleobiogeography from *Crowley* (1995), (b) the computed Late Saalian vegetation cover (B140), (c) the corresponding net primary production (in gC/m^2), (d and e) same as Figures 1b and 1c but for the LGM (B21). The types of vegetation are described on the figure. Thick lines indicate the LGM, the Late Saalian Eurasian ice sheet maximum extents and proglacial lakes (see auxiliary material).

displayed in Figure 1a. The biome distributions computed for B21 and B140 are shown on Figures 1b and 1c, respectively, together with their associated net primary productions (Figures 1d and 1e). The main differences to the *Crowley* [1995] vegetation map reside in the taiga distribution: both for the LGM and the Late Saalian, BIOME4 simulates a continuous boreal forest belt across the entire Eurasian land mass (Figures 1b and 1c).

[7] The mean annual net primary production of the forest (mixed and taiga) in Europe, Russia and Siberia ranges between 100 and 350 gC.m^{-2} during both periods, while it ranges from ≈460 to ≈630 gC.m^{-2} for the present [*Schulze et al.*, 1999; *Gower et al.*, 2001]. This suggests that the computed forest has a low density and is not productive (see discussion).

[8] The vegetation computed by the BIOME4 model for the LGM clearly differs from that of *Crowley* [1995]. The differences can result from either the use of different vegetation and AGCM models or from different LGM ice topographies: ICE-4G [*Peltier*, 1994] was used by *Crowley* [1995] and ICE-5G in the present work. In ICE-4G the Eurasian ice sheet extends into West Siberia whereas this is not the case in ICE-5G.

3.2. Impact on the Ice Sheet Surface Mass Balance

[9] For the Late Saalian, near the proglacial lakes, in European Russia and Siberia, albedo is about 30% to 50% higher in B140 than in C140 (Figure 2e) as a consequence of the perennial snow cover (not shown here). This leads to a regional cooling of −5°C to −15°C (Figure 2f) caused by the progressive disappearance of needle-leaf vegetation and

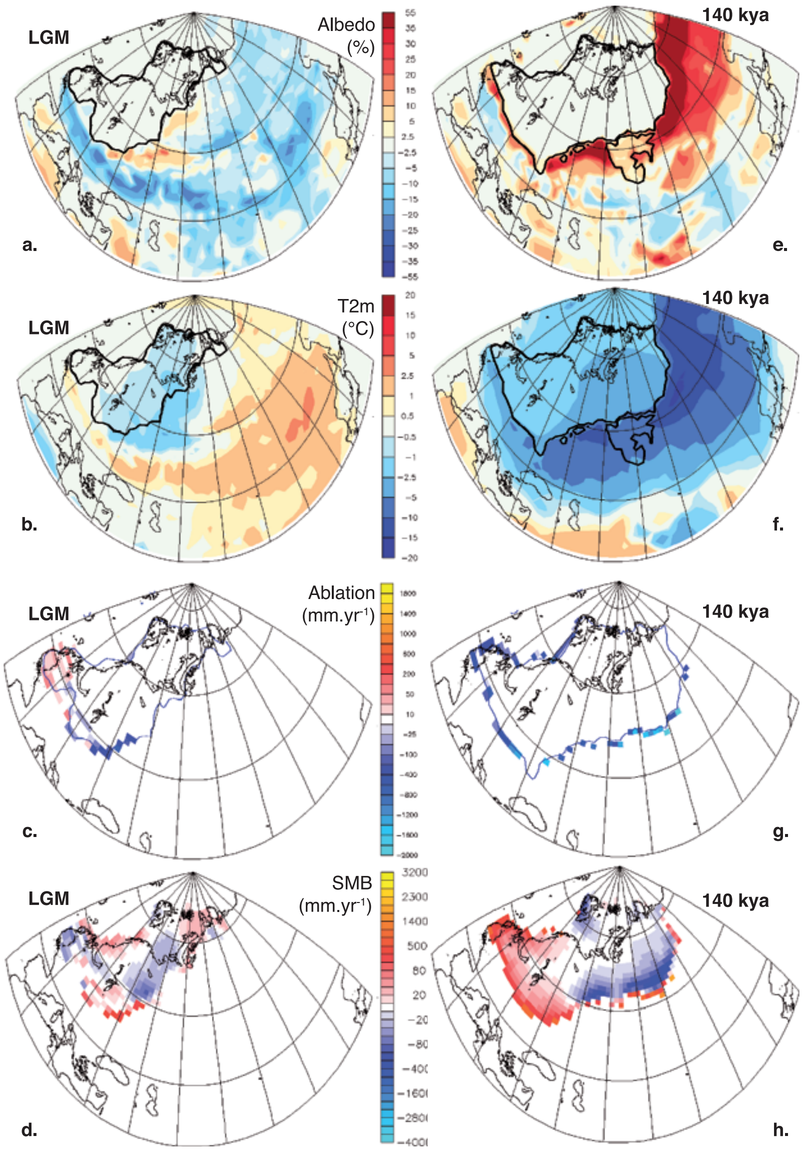

Figure 2. (a–d)Simulated climate anomalies due to vegetation changes for the LGM (B21-C21) and (e–h) the Late Saalian (B140-C140). All the climatic components are represented as annual mean anomalies between the first iteration (vegetation as on Figure 1a) and the third iteration (vegetation as on Figures 1b and 1c): albedo (Figures 2a and 2e), air surface temperature (Figures 2b and 2f), surface melt (Figures 2c and 2g) and surface mass balance (Figures 2d and 2h).

the reduction of tundra in the vicinity of the ice sheet during the three vegetation iterations (Figure 1a and 1c). This regional cooling spreads along the ice margins and southward.

[10] For the LGM, the effect of vegetation change is the opposite. The development of needle-leaf vegetation mainly over Eurasia causes a regional decrease in albedo of about 20%. This leads to a warming of 1°C to 2.5 °C in annual mean air temperature (Figures 2a and 2b). On the south-eastern margin of the ice sheet, a regional cooling of about 1°C is associated with a slight reduction of the local tree cover.

[11] The surface mass balance (SMB) of the ice sheets is reported in Table 1. The average SMB over the entire ice sheet for the Late Saalian simulations, C140 and B140, is 164 $kg.m^{-2}.yr^{-1}$ and 231 $kg.m^{-2}.yr^{-1}$ respectively. For the LGM, the simulated SMB is 210 $kg.m^{-2}.yr^{-1}$ (C21) and

Table 1. Values of the Main Components of the Surface Mass Balance of the LGM and Late Saalian Eurasian Ice Sheets[a]

($kg.m^2.yr^{-1}$)	C21	B21	C140	B140
SMB[b]	210	213	164	231*
Ablation	118	115	77	21
Tot. precip.	488	484	330	327
Snow	430	425	317	307
Evap	104	99	66	55

[a] Using Crowley's vegetation (C21 and C140 respectively), and using the BIOME4 vegetation (B21 and B140 respectively). Student t-tests have been performed to determine whether the differences observed between the results of these simulations are significant (solid star near the SMB values) or not with a probability of 5%.

[b] SMB, surface mass balance.

213 $kg.m^{-2}.yr^{-1}$ (B21). These differences, displayed on Figures 2d and 2h, are mainly a consequence of ablation changes (Figures 2c and 2g), while precipitation and evaporation remain essentially unchanged (Table 1).

4. Discussion and Conclusions

[12] In our simulations the SMB of the Late Saalian ice sheet increases when the prescribed vegetation distribution is changed from the *Crowley* [1995] LGM vegetation map to the one simulated with a global biogeography model forced by a Saalian GCM climate. This SMB increase is significant at 95%, as shown by a Student t-test (Table 1), while we do not find a significant difference in SMB due to vegetation in the LGM simulations.

[13] In the Late Saalian simulations, the lower density of vegetation in East Siberia and along the ice margins causes a regional cooling of about −10°C, spreading westward and southward. In this region, SMB becomes positive due to reduced ablation (Figure 2g and Table 1). The local cooling also induces a perennial snow cover, which contributes to a more positive SMB through the higher albedo (Figure 2a). The effect of the vegetation distribution change is not the same for LGM simulations because the positive SMB value simulated in Russia is balanced by the negative SMB caused by the replacement of grass with taiga in Western Europe.

[14] During the LGM, contrary to ICE-4G used by *Crowley* [1995], Siberia is entirely ice-free in ICE-5G. Consequently, vegetation changes in this area cannot affect the SMB of the ICE-5G ice sheet as much as for the Late Saalian. Indeed, the large Late Saalian ice volume and extent cause an initial cooling that is reinforced by vegetation feedbacks.

[15] Compared to *Crowley* [1995] our LGM simulated climate allows for the growth of a low density mixed forest over Europe. This agrees with the review of *Willis and van Andel* [2004] who show that some refugial for forest-type vegetation existed in Central and Eastern Europe during the LGM. According to *Tarasov et al.* [2000] taiga developed in European Russia and in Siberia but slightly southward of their present-day limits. Cool mixed forest also developed in Mongolia and on the eastern part of the Black Sea, which is consistent with our reconstruction. However, our reconstructions allow for more mixed forest near the LGM ice sheet margins than observed in the pollen data.

[16] The influence fluctuations in SST have on vegetation in our AGCM experiments must be considered with caution, particularly concerning the Late Saalian simulation experiments as these are forced by LGM SST. This will be the object of further studies. In any case, the most important result of this work is that, although a simulated LGM vegetation distribution should be a valid approximation to model previous ice ages, it appears that using an iteratively calculated Late Saalian vegetation map leads to a significantly different simulation of the climate for that period and directly impacts ice sheet dynamics through the consequent variations of surface mass balance. This highlights the need to compute vegetation using fully coupled atmosphere-vegetation models that can capture these dynamics interactions.

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References

Berger, A., and M. Loutre (1991), Insolation values for the climate of the last 10 millions years, *Quat. Sci. Rev.*, *10*(4), 297–317.

Brovkin, V., S. Levis, M.-F. Loutre, M. Crucifix, M. Caussen, A. Ganopolski, C. Kubatzi, and V. Petoukhov (2003), Stability analysis of the climate-vegetation system in the northern high latitudes, *Clim. Change*, *57*(1–2), 119–138.

Charney, J. (1975), Dynamics of deserts and drought in the Sahel, *Q. J. R. Meteorol. Soc.*, *101*(428), 193–202.

Colleoni, F., G. Krinner, M. Jakobsson, V. Peyaud, and C. Ritz (2009), Influence of regional parameters on the surface mass balance of the Eurasian ice sheet during the peak Saalian (140 kya), *Polar Res.*, in press.

Crowley, T. (1995), Ice age terrestrial carbon changes revisited, *Global Biogeochem. Cycles*, *9*(3), 377–389.

Crowley, T., and S. Baum (1997), Effect of vegetation on an ice-age climate model simulation, *J. Geophys. Res.*, *102*(D14), 16,463–16,480.

Crucifix, M., and C. Hewitt (2005), Impact of vegetation changes on the dynamics of the atmosphere at the Last Glacial Maximum, *Clim. Dyn.*, *25*(5), 447–459.

Gower, S., O. Krankina, R. Olson, M. Apps, S. Linder, and C. Wang (2001), Net primary production and carbon allocation patterns of boreal forest ecosystems, *Ecol. Appl.*, *11*(5), 1395–1411.

Hourdin, F., et al. (2006), The LMDZ4 general circulation model: Climate performance and sensitivity to parametrized physics with emphasis on tropical convection, *Clim. Dyn.*, *27*(7–8), 787–813.

Kaplan, J. O., et al. (2003), Climate change and Arctic ecosystems: 2. Modeling, paleodata-model comparisons, and future projections, *J. Geophys. Res.*, *108*(D19), 8171, doi:10.1029/2002JD002559.

Kleidon, A., K. Fraedrich, and A. Heimann (2000), A green planet versus a desert world: Estimating the maximum effect of vegetation on the land surface climate, *Clim. Change*, *44*(4), 471–493.

Krinner, G., J. Mangerud, M. Jakobsson, M. Crucifix, C. Ritz, and J. Svendsen (2004), Enhanced ice sheet growth in Eurasia owing to adjacent ice-dammed lakes, *Nature*, *427*(6973), 429–432.

Krinner, G., O. Boucher, and Y. Balkanski (2006), Ice-free glacial northern Asia due to dust deposition on snow, *Clim. Dyn.*, *27*(6), 613–625.

Kubatzki, C., and M. Claussen (1998), Simulation of the global biogeophysical interactions during the Last Glacial Maximum, *Clim. Dyn.*, *14*(7–8), 461–471.

Levis, S., J. Foley, and D. Pollard (1999), Co_2, climate, and vegetation feedbacks at the Last Glacial Maximum, *J. Geophys. Res.*, *104*(D24), 31,435–31,669.

Mahowald, N., K. Kohfeld, M. Hansson, Y. Balkanski, S. P. Harrison, I. C. Prentice, M. Schulz, and H. Rodhe (1999), Dust sources and deposition during the Last Glacial Maximum and current climate: A comparison of model results with paleodata from ice cores and marine sediments, *J. Geophys. Res.*, *104*(D13), 15,895–15,916.

Ohmura, A., M. Wild, and L. Bengtsson (1996), A possible change in mass balance of Greenland and Antarctic ice sheets in the coming century, *J. Glaciol.*, *9*(9), 2124–2135.

Paul, A., and C. Schäfer-Neth (2003), Modeling the water masses of the Atlantic Ocean at the Last Glacial Maximum, *Paleoceanography*, *18*(3), 1058, doi:10.1029/2002PA000783.

Peltier, W. (1994), Ice age paleotopography, *Science*, *265*(5169), 195–201.

Peltier, W. (2004), Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE, *Annu. Rev. Earth Planet. Sci.*, *32*, 111–149.

Petit, J. R., et al. (2001), Vostok ice core data for 420000 years, http://users.aims.ac.za/irina/dustVostok.txt, World Data Cent. Paleoclimatology, Boulder, Colo.

Peyaud, V. (2006), Role of the ice sheet dynamics in major climate changes, Ph.D. thesis, Lab. de Glaciol. et de Geophys. de l'Environ., Univ. Grenoble I, Grenoble, France.

Schulze, E., et al. (1999), Productivity of forests in the Eurosiberian boreal region and their potential to act as a carbon sink—A synthesis, *Glob. Change Biol.*, *5*(6), 703–722.

Spahni, R., et al. (2005), EPICA Dome C CH_4 Data to 650KYrBP, ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/epica_domec/edc-ch4-2005-650k.txt, World Data Cent. Paleoclimatology, Boulder, Colo.

Svendsen, J., et al. (2004), Late Quaternary ice sheet history of northern Eurasia, *Quat. Sci. Rev.*, *23*(11–13), 1229–1271.

Tarasov, P., et al. (2000), Last Glacial Maximum biomes reconstructed from pollen and plant macrofossil data from northern Eurasia, *J. Biogeogr.*, *27*(3), 609–620.

Willis, K., and T. van Andel (2004), Trees or no trees? The environments of central and eastern Europe during the last glaciation, *Quat. Sci. Rev.*, *23*(23–24), 2369–2387.

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