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Climate of the Past Discussions

Early last glacial maximum in the Southern Central Andes reveals northward shift of the westerlies at ∼39 ka

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Abstract

The latitudinal position of the southern westerlies has been suggested to be a key parameter for the climate on Earth. According to the general notion, the southern westerlies were shifted equatorward during the global Last Glacial Maximum (LGM: ∼24–18 ka), resulting in reduced deep ocean ventilation, accumulation of "old dissolved carbon", and low atmospheric CO_2 concentrations. In order to test this notion, we applied surface exposure dating on moraines in the Southern Central Andes, where glacial mass balances are particularly sensitive to changes in precipitation, i.e. to the latitudinal position of the westerlies. Our results provide robust evidence that the maximum glaciation occurred already at ∼39 ka, significantly predating the global LGM. This questions the role of the westerlies for atmospheric CO_2, and it highlights our limited understanding of the forcings of atmospheric circulation.

1 Introduction

The southern westerlies are an important driver for upwelling around Antarctica and deep ocean ventilation (Toggweiler et al., 2006). As atmospheric CO_2 is constantly and naturally removed in large quantities by marine organisms, and the respired CO_2 is accumulating in the deep ocean, changes in upwelling might have a substantial affect on the concentration of atmospheric CO_2 and climate on Earth. It has been suggested that a more equatorward position of the westerlies during glacials resulted in a weakening of the northward Ekman transport of surface waters, reduced deep ocean ventilation, and low levels of atmospheric CO_2 (Toggweiler et al., 2006). This hypothesis builds on the general notion that the westerlies were shifted northward during the global LGM, which has been inferred from terrestrial paleoecological and marine records off Chile (Heusser, 1989; Stuut and Lamy, 2004). However, there is a long-standing controversy regarding the interpretation of pollen records in Patagonia (Markgraf, 1989; Markgraf et al., 1992), and marine records may reflect a complex mixture of regional and local

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up-welling and environmental signals (Stuut et al., 2006). Additionally, climate modeling results do not show significant shifts of the westerlies during the global LGM (Rojas et al., 2009).

In order to contribute to the reconstruction of the position of the southern westerlies, we applied ^{10}Be surface exposure dating on moraines in the Southern Central Andes. Whereas glaciers in Patagonia always received plenty of precipitation and reached their maximum extents at times of low temperatures, i.e. in-phase with the global LGM (Kaplan et al., 2008; Douglass et al., 2006), glacier mass-balances in more arid environments, such as the Southern Central Andes, become more precipitation-sensitive, and the glacial chronologies there thus also reflect changes in the position of the westerlies (Kull et al., 2002, 2008; Wäger et al., 2010).

2 Geographical setting and surface exposure dating

The Southern Central Andes north of ~40° S are characterized by strong precipitation gradients in north-south and east-west directions (Fig. 1). They are therefore an ideal location to record latitudinal shifts of the westerlies. We applied ^{10}Be surface exposure dating in the Rucachoroi Valley, Central Argentina (39°14′ S, 71°11′ W) (Fig. 2). The valley is located east of the Andean divide, but receives most of its precipitation from the Pacific related to the seasonal northward shift of the westerlies in austral winter. Weather station data from Bariloche (41°15′ S) indicate ~800 mm mean annual precipitation and 8 °C mean annual temperature at 840 m a.s.l. (above sea level). No glaciers exist today in the Rucachoroi Valley despite summits reaching > 2000 m a.s.l. Extensive glaciation in the past is documented by the U-shaped valley form, glacial over-deepening (formation of Lake Rucachoroi at 1230 m a.s.l.), and a prominent right-lateral moraine merging into a lateral-frontal moraine at ~1200 m a.s.l. (Fig. 2).

We sampled and analyzed seven boulders from the prominent lateral and lateral-frontal moraine in order to determine the timing of the maximum glaciation, as well as six additional boulders and polished bedrock from further up-stream to constrain the

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deglaciation history (Fig. 2). The sampling strategy followed standard guidelines, collecting ∼0.5 kg of rock material from the flat top of large, stable boulders or polished bedrock surfaces. Exact sample locations were determined using a handheld GPS and documented with photographs. Sample preparations followed standard laboratory techniques including separation of quartz, addition of a ^{9}Be carrier, dissolution in HF, and chromatographical purification of beryllium. The ^{10}Be/^{9}Be AMS measurements were conducted at the ETH AMS facility in Zurich. We used the CRONUS-Earth online calculator (http://hess.ess.washington.edu) applying the scaling model of Lifton et al. (2005) to calculate the surface exposure ages (all sample data are provided in the supplementary Table 1). Note that our conclusions are independent of the choice of the scaling model (see supplementary Table 2).

3 Results

The exposure ages from the moraines range from 30.2 ± 3.0 ka to 38.8 ± 3.9 ka (Fig. 2). The observed scatter mainly reflects geological uncertainties due to post-depositional processes, and the generally low probability of pre-exposure justifies the application of the "oldest age model" (Putkonen and Swanson, 2003; Zech et al., 2005). Following this concept, the oldest boulder from a moraine is the best available minimum estimate for the true deposition age, unless it is a statistical or stratigraphic outlier. Accordingly, we can infer that the maximum ice extent in the Rucachoroi Valley occurred at ∼39 ka, clearly pre-dating the global LGM.

The exposure ages of 17.9 ± 1.8 ka and 14.8 ± 1.5 ka from the samples RU31 and RU32 (Fig. 2) show that the glacier continued to occupy the upper part of the Rucachoroi Valley and started to retreat beyond the Rucachoroi Lake only after the global LGM. The absence of moraines other than the prominent ones dated to ∼39 ka likely indicates that no prominent glacial re-advances occurred between ∼39 ka and ∼18 ka. Deglaciation of the upper part of the Rucachoroi Valley occurred after ∼18 ka, and most of the valley became ice-free by ∼15.5 ka (RU11: 15.5 ± 1.5 ka, RU21: 15.5 ± 1.5 ka).

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Only small, sporadic cirque moraines provide geomorphological evidence for minor glacial readvances and climate reversals during the Lateglacial. One respective exposure age of 12.2 ± 1.2 ka (RC12) has been obtained so far, but will have to be corroborated in future studies.

4 Comparison with other paleoclimate proxies

The early local LGM in the Rucachoroi Valley and deglaciation after ~18 ka is consistent with findings from the Chilean Lake District (CLD) (Fig. 1). There, extensive radiocarbon dating showed that the piedmont glaciers reached maxima at ca. 29.6, 26.9, 23.1, 21.0, 14.9 and 13.9 ^{14}C ka BP (~35, 31, 28, 25, 18 and 17 cal ka BP), with earlier advances being notably more extensive in the northern CLD (Denton et al., 1999; Lowell et al., 1995). Further north, in the Mendoza Andes (~33° S), Argentina, the "Penitentes Till" is constrained by a minimum thermo-luminescence age of 31.0 ± 3.1 ka, as well as a U/Th age of 38.3 ± 5.3 ka from travertine (Espizua, 2004). Ultimately, exposure ages from the Dona Rosa Valley (~31° S), Northern Chile, have shown that the maximum datable advance there occurred at ~39.0 ± 4.1 ka (Zech et al., 2007, 2008). Thus, in summary, there is inevitable evidence that the local LGM in the Southern Central Andes from 30 to 40° S significantly predated the global LGM on both the western and eastern side of the divide. Given the precipitation sensitivity of glacier mass balances (Kull et al., 2002, 2008; Wäger et al., 2010), the westerlies must have provided more moisture and were most likely shifted equatorward at ~39 ka.

Our interpretation of the glacial chronologies is corroborated by pollen records from ~25° S that indicate increased winter precipitation between 40–33 ka and between 24–17 ka (Maldonado et al., 2005), and by lake sediments from Central Chile that show high lake levels of Laguna Tagua Tagua (34.5° S) between ~40 and 17 ka (Valero-Garcés et al., 2005). The circumpolar nature of the westerlies' shift should be investigated in more detail in the future, but extensive glacial advances, high lake levels and river runoff maxima are documented, for example, also in Southern Australia at

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~35 ka (Barrows et al., 2001; Kemp and Spooner, 2007). There, an even more extensive glacial advance has been dated to ~60 ka, which has not yet been identified in the Southern Central Andes.

5 Discussion of the forcings of the westerlies

Our results question the general notions regarding the forcings responsible for the latitudinal position of the southern westerlies. Traditionally, low Antarctic temperatures and extensive sea ice have been invoked to push the westerlies northward during the global LGM (Heusser, 1989; Stuut and Lamy, 2004). This is difficult to reconcile with our findings, as neither sea ice was particularly extensive at ~39 ka, nor were Antarctic temperatures at a minimum (Fig. 3a,c,e). Furthermore, we can rule out seasonal insolation/temperature as a prominent forcing, because winter insolation is high between ~40 and 20 ka (Fig. 3d), which would favor a less pronounced seasonal northward shift of the westerlies and is at odds with more humid conditions documented for that very time period.

In search for other potential forcing mechanisms, we found an intriguing resemblance of the latitudinal position of the westerlies with changes in cosmic ray flux (Fig. 3b). High fluxes at ~60 ka and between ~40 and 25 ka, can be inferred from cosmogenic nuclides produced in the atmosphere, such as ^{10}Be, ^{14}C and ^{36}Cl (Christl et al., 2007; Hughen et al., 2004), and can be related to periods with a weaker geomagnetic field (e.g. the Laschamp event at ~39 ka). It has been suggested that cosmic-ray-induced ionization in the atmosphere can directly affect cloud formation and the atmospheric circulation (Usoskin and Kovaltsov, 2008; Burns et al., 2008). Alternatively, past natural changes in the cosmic ray flux could have sufficiently affected the atmospheric chemistry and in particular ozone concentrations. Consequences for the position of the westerlies would then have to be expected in analogy to the southward shift of the westerlies observed during recent decades, which has been attributed to the "anthropogenic" destruction of stratospheric ozone (Son et al., 2008). We have to emphasize here, however, that potential mechanisms of cosmic ray – climate linkages remain highly controversial, and that we were not able to robustly identify the forcing or mechanism responsible for the northward shift of the westerlies at ∼39 ka.

6 Conclusions

The glacial chronologies in the Southern Central Andes provide robust evidence for an early last glacial maximum at ∼39 ka, which documents increased precipitation at that time and a northward shift of the southern westerlies. Our understanding of the forcings for this shift remains incomplete, and the coincidence with the Laschamp event will fuel discussions concerning possible cosmic ray – climate linkages. These linkages should be further investigated, and future global climate modeling studies might have to include changes in atmospheric chemistry.

Our findings also have major implications regarding the role of the westerlies in the carbon cycle. At first glance, low atmospheric CO_2 concentrations between ∼40 and 20 ka seem to corroborate the proposed link between equatorward westerlies, reduced deep ocean ventilation, and low levels of atmospheric CO_2 (Toggweiler et al., 2006). However, CO_2 levels had already dropped significantly at ∼70 ka, and no dramatic changes occurred at ∼39 ka (Fig. 3f) (Ahn and Brook, 2008). We conclude that latitudinal shifts of the westerlies did not exert dominant control on atmospheric CO_2 concentrations on glacial-interglacial timescales, which is in agreement with recent modeling studies (Tschumi et al., 2008). In fact, it has been impossible so far to find the pool of "old" radiocarbon supposedly trapped in the glacial deep ocean. This pool would be required to corroborate the "ocean hypothesis", i.e. the notion that CO_2 was trapped in the deep glacial ocean (Broecker and Barker, 2007). In light of these inconsistencies, one should remain open-minded to alternative hypotheses with regards to the glacial-interglacial atmospheric CO_2 changes, e.g. changes in the terrestrial carbon cycle (Zech et al., 2010).

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Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/6/1991/2010/cpd-6-1991-2010-supplement.pdf.

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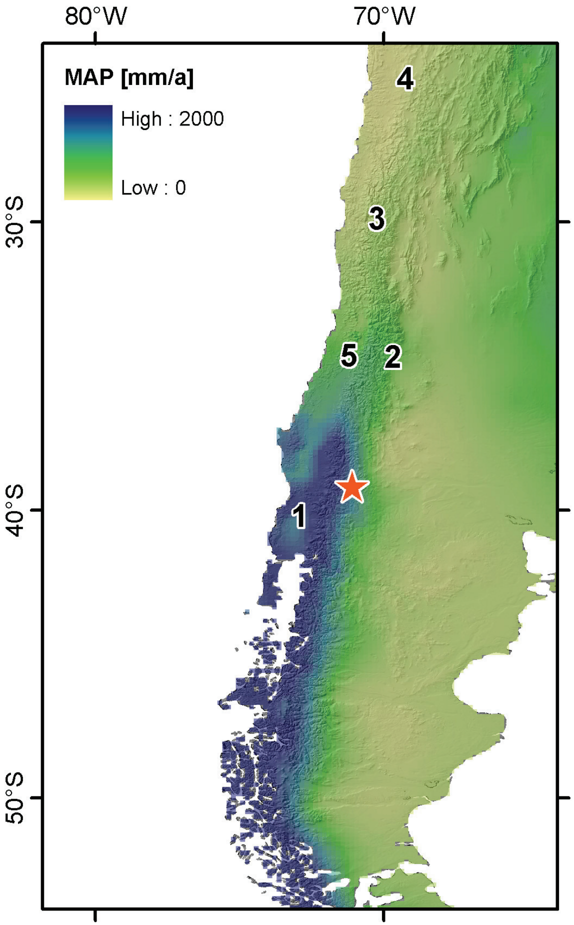

Fig. 1. Location of the research area, the Rucachoroi Valley (star), and other sites discussed in the text. 1 – Chilean Lake District, 2 – Mendoza Andes, 3 – Cordon de Dona Rosa, 4 – Atacama Desert, 5 – Laguna Tagua Tagua. MAP=mean annual precipitation.

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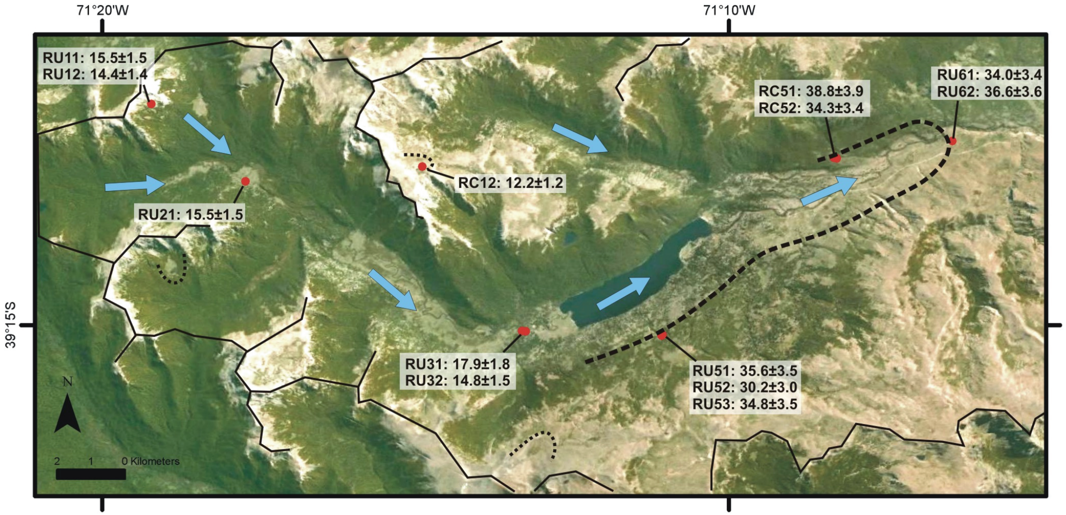

Fig. 2. Landsat image of the Rucachoroi Valley with sampling locations and surface exposure ages [ka]. Hollow arrows indicate the former ice flow direction, the dotted line marks the prominent lateral and lateral-frontal moraine, and dashed lines mark cirque moraines. Continuous thin lines demarcate the catchment crests.

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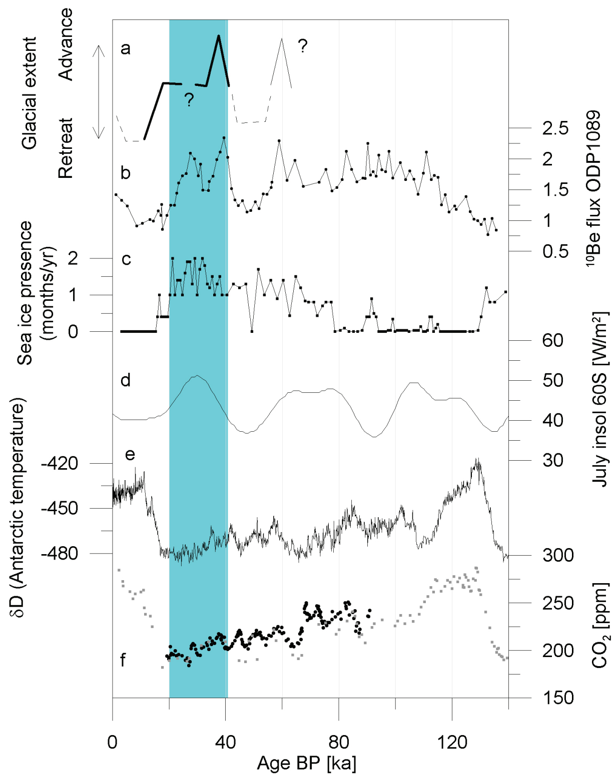

Fig. 3. Comparison of the glacial chronology in the Southern Central Andes in the paleoclimatic context. **(a)** Glacial extents, indicating the northward shift of the westerlies, **(b)** changes in the cosmic ray flux (transport corrected ^{10}Be flux [at cm^{-2} ka^{-1}]×10^9) (Christl et al., 2007), **(c)** sea ice duration around Antarctica (Crosta et al., 2004), **(d)** austral winter insolation at 60° S, **(e)** deuterium from the Vostok ice core as proxy for Antarctic temperatures (Petit et al., 1999), and **(f)** atmospheric CO_2 concentrations (Petit et al., 1999; Ahn and Brook, 2008).