The Little Ice Age in southern Patagonia: Comparison between paleoecological reconstructions and downscaled model output of a GCM simulation

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The "Little Ice Age" (LIA) usually refers to climatic anomalies over the northern hemisphere between the 13th and mid-19th century. The LIA is well documented in northern Europe and America, where a huge variety of chronicles, historical documents, proxy-based reconstructions and also temperature measurements indicate cooler and wetter conditions. Within the LIA, a period with even lower temperatures was the Maunder Minimum (MM; ~1645–1715). Proxy and modeling studies point to a prominent influence of solar forcing causing the MM (Eddy, 1976; Zorita et al., 2004). At the beginning of the last millennium, a period of warmer conditions, especially over Europe, has been documented; the so-called Medieval Warm Period (MWP; ca. 9th–13th centuries) (Jones et al., 2001; Osborn and Briffa, 2006).

For the southern hemisphere, especially for the mid- and high-latitudes, no documentary evidence of these climatic events is available due to the large oceanic areas and the sparse settlement of the continental regions during these periods. Additionally, the number of proxy-based reconstructions is fragmentary.

Here, results of a simulation with a general circulation model (GCM) with varying forcing factors (solar, volcanic, greenhouse gases) of the last 1000 years are compared to proxy data for southern South America. The main goal was to examine if, and to what extent, the LIA could be identified in paleohydrological proxies in southeastern Patagonia. In the GCM simulation the LIA is indicated by a pronounced decline in northern hemispheric temperatures in the period between 1500 and 1900 (cf., von Storch et al., 2004).

The GCM used had quite a coarse resolution (ca. 300 x 300 km). Small-scale processes, specifically those related to hydrological variables, are not realistically reproduced. To overcome this, an additional statistical downscaling technique was implemented, relating the large-scale circulation of the GCM, which is more realistically reproduced than hydrological variables, with local precipitation over South America. The downscaling model is based on principal component regression analysis (Luterbacher et al., 2002). To set up the

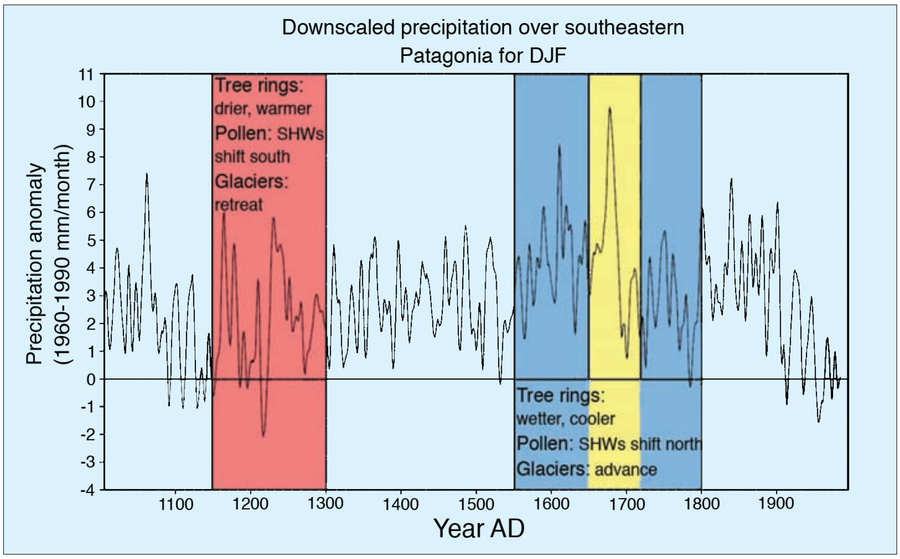

*Figure 1: Downscaled precipitation for south-eastern Patagonia for austral summer (DJF) (MWP = **red**, LIA = **blue**, MM = **yellow**). Note the wetter conditions during the LIA, especially the MM compared to the most recent period 1960–1990 indicated by the zero line. Climatic information derived from proxy data is given for the respective anomalous periods.*

downscaling models, the leading five sea level pressure (SLP) principal components of the National Centers for Environmental Prediction (NCEP)-reanalysis (Kistler et al., 2001) over southern South America were linked to precipitation over southeastern Patagonia (Beck et al., 2004) for the period 1951–2000 by means of multiple linear regression. (Principal components reflect the temporal evolution of eigenvectors (=Empirical Orthogonal Functions, EOFs) of the covariance-matrix, e.g., from SLP anomaly fields.) Although the downscaling models describe only part of the observed precipitation variability, their performance is still high enough to be used for downscaling the large-scale circulation of the GCM. To obtain the simulated SLP principal components of the last thousand years, the observed NCEP-EOFs were projected onto the simulated SLP anomaly fields. In the last step, these simulated SLP-principal components were used to reconstruct precipitation over southeastern Patagonia. Downscaling models also allow investigation of the physical mechanisms that explain precipitation changes related to changes in the Southern Hemispheric Westerlies (SHWs). For southeastern Patagonia, the downscaling models show that stronger SHWs are linked to higher precipitation and vice versa (Wagner et al., 2007).

The downscaled precipitation for southeastern Patagonia for austral summer (DJF) is shown in Figure 1. Results for the different historical periods are compared with the most recent period (REC), i.e., 1960–1990. According to Figure 1, the LIA, and here especially the MM, is a time of wetter conditions in Patagonia compared to REC, with precipitation anomalies of +4.1 and +3.4 mm/month for the MM and the LIA, respectively. Precipitation differences are statistically different at the 5% level. Conversely, most periods during the MWP show conditions that are only slightly higher compared with REC (+1.7 mm/month). Here precipitation differences are not statistically significant at the 5% level.

These precipitation fluctuations can be attributed to latitudinal shifts of the SHWs. A mechanism that possibly explains changes in SHWs relates to the extension of the sea ice south of South America (not shown): During the MWP, the SHWs shifted further to the south due to a decrease in sea ice cover. As a consequence, the SHWs were located over southern Patagonia. The volume of sea ice increased during the LIA, especially around the MM and the SHWs shifted further northward again.

Downscaled results of the GCM simulation are also in accordance with results from dendroclimatological investigations (Villalba, 1990; Lara and Villalba, 1993) that show wetter conditions in Patagonia during the LIA. Again, these changes can be attributed to shifts of the SHWs. Additionally, lacustrine investigations (Haberzettl, 2006; Stine and Stine, 1990) indicate lower temperatures and wetter conditions in Patagonia during the LIA. Pollen-based results point to vegetation-type changes from dry to wet species. The latter can also be attributed to shifts in the SHWs (Mayr et al., 2007). Further, the analysis of glaciers and moraines in Patagonia show extensive glaciation during the LIA (Harrison et al., 2006, Koch and Kilian, 2005, Thompson et al., 1986).

Therefore, the comparison between proxy-based reconstructions and results from the GCM simulation show that both, model and proxy data indicate a climatically anomalous period between the mid-16th and 19th century over southern South America. This suppors the hypothesis that the LIA, as indicated in proxy based and modeled northern hemispheric temperatures, is also reflected in hydrological variables over parts of the southern hemisphere.

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Three-dimensional radiocarbon modeling: A tool to assess the last glacial ocean circulation and radiocarbon chronologies

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At the Last Glacial Maximum (LGM), the overturning circulation of the ocean was probably quite different from today. The changes are still debated, as the current generation of coupled climate models arrive at contradictory results (e.g., Otto-Bliesner et al., 2007), and paleoceanographers face the problem of extracting robust and unambiguous information from proxy data.

In an attempt to reconcile observations with modeling, we simulated the distribution of marine radiocarbon (^{14}C) at the LGM, using a three-dimensional ocean general circulation model connected with an atmospheric radiocarbon reservoir (Butzin et al., 2005). The ocean model has an effective horizontal resolution of 3.5°, with a vertical resolution of 22 depth levels, and it is forced with atmospheric fields, which were derived in previous glacial climate simulations (as described by Prange et al., 2004). In a series of sensitivity studies with constant boundary conditions, we explored the influence of sea surface temperatures, sea ice extent, wind stress, and Antarctic sea ice formation on the glacial ^{14}C distribution and on the meridional overturning circulation (MOC).

Our simulations reveal a crucial influence of the background climate conditions on the results. The best agreement of modeled ^{14}C distributions with glacial ^{14}C observations is for a model run with significant MOC changes in the Atlantic, where the North Atlantic Deep Water (NADW) shallows to a depth above about 2 km and weakens by about 40% compared to the present day. Conversely, Antarctic Bottom Water flow intensifies and compensates for the weakened NADW transport into the South Atlantic. As a consequence, the modeled abyssal glacial Atlantic is depleted in ^{14}C (Fig. 1), very cold and very saline. These results are in line with proxy data evidence (see Lynch-Stieglitz et al., 2007, for a review).

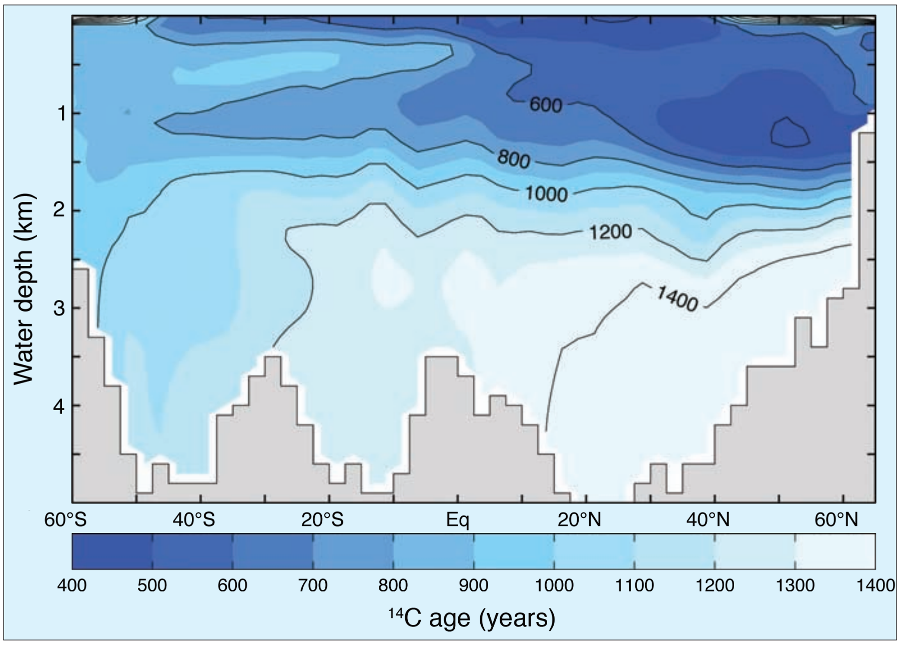

Figure 1: Radiocarbon age in the western Atlantic (along the GEOSECS track) according to simulations for the Last Glacial Maximum (Butzin et al., 2005).

Radiocarbon concentrations in environmental samples are frequently quoted in the form of ages relative to atmospheric ^{14}C values. Applying the law of radioactive decay, high ^{14}C concentrations translate into low ^{14}C ages, and vice versa. Radiocarbon concentrations of the present-day surface ocean correspond to an apparent marine reservoir ^{14}C age (MRA) of about 400 yr in the global mean, and range from about 300 yr in the subtropics to 1000 yr at high latitudes (e.g., Key et al., 2004). Our simulations indicate generally higher MRAs for the LGM (Fig. 2). This reflects slower uptake of ^{14}C by the glacial ocean, which is predominantly due to the reduced partial pressure of atmospheric CO_2