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Patagonian Glacier Response During the Late Glacial–Holocene Transition

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Whether cooling occurred in the Southern Hemisphere during the Younger Dryas (YD) is key to understanding mechanisms of millennial climate change. Although Southern Hemisphere records do not reveal a distinct climate reversal during the late glacial period, many mountain glaciers readvanced. We show that the Puerto Bandera moraine (50°S), which records a readvance of the Southern Patagonian Icefield (SPI), formed at, or shortly after, the end of the YD. The exposure age (10.8 ± 0.5 thousand years ago) is contemporaneous with the highest shoreline of Lago Cardiel (49°S), which records peak precipitation east of the Andes since 13 thousand years ago. Absent similar moraines west of the Andes, these data indicate an SPI response to increased amounts of easterly-sourced precipitation—reflecting changes in the Southern Westerly circulation—rather than regional cooling.

First detected in pollen records from northern Europe, the Younger Dryas (YD) chronozone is perhaps best expressed in Greenland ice cores (1) that show an abrupt return to near-glacial conditions in the North Atlantic region during the last deglaciation between 12.9 and 11.6 thousand years ago (ka). Less extreme, but extensive, cooling occurred throughout the Northern Hemisphere (2). Comparison of temperature records from Greenland and Antarctic ice cores during the last deglaciation indicate antiphased behavior, however (3); the Antarctic Cold Reversal (ACR) preceded the YD interval and Antarctic warming occurred during the YD, peaking at ~11 ka. Determining whether the Southern Hemisphere mid-latitudes follow a North Atlantic or an Antarctic signal remains key to deciphering the mechanisms responsible for millennial and abrupt climate change (4).

In general, climate records from New Zealand and Patagonia lack evidence of a distinct climate reversal during the late glacial period [see the supporting online material (SOM) text]. Yet there is clear evidence for prominent glacial readvances in both New Zealand’s Southern Alps (5, 6) and the Southern Andes after ~15 ka (7). In New Zealand, the Waiho Loop moraine, which was previously inferred to be of YD age on the basis of 14C ages of reworked wood, may be significantly younger in accordance with cosmogenic surface-exposure ages of moraine boulders (8, 9). 14C ages provide only broadly limiting constraints on late glacial advances in Patagonia. Thus, both the timing and synchrony of Southern Hemisphere glacial readvances remain poorly constrained.

The Puerto Bandera moraines at Lago Argentino, Argentina (50°S), consist of two terminal moraine belts (PB I and PB II) that can be distinguished on the basis of field observations (10). The moraines occur along both the northern and southern shore of the lake with the younger (PB II) moraine cresting the older (PB I) near the present shoreline (Fig. 1C). Lying within the Patagonian steppe, where precipitation is currently only ~200 mm/year, the moraines record readvances of Southern Patagonian Icefield (SPI) outlet glaciers that extended 40 km beyond the nearest present-day ice margins.

Three 14C dates of peat overlying gravel from an abandoned outlet channel in the nearby Brazo Rico moraine (Fig. 1C) with a weighted mean age of 11.7 ± 0.3 ka (10–12) have been taken as a minimum age of the Puerto Bandera moraines (13). Although the ages are consistent with a YD age for the Brazo Rico moraine, Mercer considered this interpretation unlikely because it requires a very rapid retreat of the ice front at the end of the YD (11); peat could not begin to accumulate in the outlet channel until the glacier had retreated to the position of the present Perito Moreno Glacier, thereby opening a lower outlet to Lago Argentino along its terminus (Fig. 1C). Strelin and Malagnino report 14C ages of reworked peat in lateral moraines in Brazo Norte (Fig. 1C) (10). An age of 15.5 ± 2.4 ka was obtained from a PB I moraine and an age of 12.9 ± 2.1 ka was obtained from a PB II moraine. The 14C ages of reworked peat show that the SPI had retreated within the Cordillera at these times and indicate that the terminal Puerto Bandera moraines record a large-scale readvance of the SPI.

To better constrain the age of the Puerto Bandera moraines and to evaluate Southern Hemisphere climate during the YD interval, we determined the exposure ages of 18 moraine boulders using cosmogenic 36Cl and 10Be. Samples were collected from the outermost moraine crests on both the northern and southern side of the lake. Fifteen samples are from PB I and three samples are from PB II (Fig. 1C). Boulders were selected on the basis of size, shape, quartz content (for the 10Be samples), and lack of weathering in order to reduce geologic uncertainties. The 36Cl and 10Be production rates have been scaled for elevation, latitude, and atmospheric pressure (14). Adjustments for erosion and secular variation of the magnetic field were unnecessary. We estimate that uncertainties in our exposure ages, including scaling factors, are ~6% (15).

The arithmetic means of the 10Be and 36Cl exposure ages are 10.8 ± 2.1 ka and 10.8 ± 2.9 ka, respectively (Table 1). More involved statistical treatment relies on the assumption that the exposure ages comprise a normal distribution, specifically, that all samples have an identical simple exposure history and that scatter in the ages results from normally distributed analytical uncertainties. We tested this assumption using a χ2 analysis. We found the youngest 36Cl and 10Be exposure ages to be outliers based on the low probability that the samples come from a single normal distribution (16). The weighted mean of the remaining 10Be ages is 10.8 ± 0.6 ka; that of the remaining 36Cl ages is 10.9 ± 0.9 ka (Table 1 and tables S2 and S3). All 16 samples yielded an inverse-variance weighted mean age of 10.8 ± 0.5 ka (the mean square weighted deviation is 0.80). Given that the scatter in the ages can be attributed mostly to normally distributed analytical errors, we inferred that...
the moraines stabilized within several hundred years (15).

We interpreted the exposure age of the PB I moraine as the end of deposition and the start of ice recession and, thus, a fundamental change in the regional climate. The magnitude of the climate change represented by the PB I glacial advance is indicated by the equilibrium-line altitude of scaling uncertainty that is typically assumed (±10%), the exposure age would fall within the end of the YD; this would not alter our conclusions. In any case, our results are inconsistent with previous interpretations that the PB I moraine is older than the YD, because of limiting 14C dates of neighboring moraines (10, 17). Considering the limiting 14C age of 12.9 ± 2.1 ka, the duration of the PB I readvance was only 1000 to 2000 years. As shown below, this period is characterized in regional climate records by its increasing precipitation and temperature, which culminated ~11 ka.

The exposure age of the PB I moraine boulders coincides with the 14C age of the highest shoreline at Lago Cardiel (49°S), a closed lake basin east of the Andes (Fig. 1, A and B). Lake levels rose from near desiccation (~73 m below present) after 13.1 ± 0.2 ka (18) and peaked at levels 55 m above the present shoreline about 10.8 ± 0.3 ka (19, 20) (Fig. 2F). The desiccation event, which occurred near the end of the ACR, indicates extreme aridity east of the Andes during that time. The high lake levels, which are not seen either during the late glacial period or after the middle Holocene, indicate that precipitation east of the Andes peaked at around 11 ka. West of the Andes, but north of the study area (41°S), an alkenone-based sea surface temperature (SST) record at Ocean Drilling Program (ODP) site 1233, from a high-sedimentation-rate core on the continental slope (21) (Fig. 1, A and B, and Fig. 2C), closely resembles the temperature records from Antarctic ice cores (Figs. 1A and 2G). Temperature rose through the YD and reached a maximum by 12 ka. Salinity rose through the ACR and fell through the YD with minimum values coinciding with the maximum lake levels at Lago Cardiel (Fig. 2, E and F). The salinity decrease, as well as the high Fe concentrations (Fig. 2D), is consistent with increased rainfall, erosion, and runoff into fjords west of the southern Andes and the Patagonian ice fields.

Pollen and charcoal records from Patagonia between 38°S and 55°S suggest different climate histories for different latitude bands (20). Before 11 ka, maximum precipitation occurred to the north, whereas the middle and southern latitudes were quite dry and somewhat cooler. Between 11 and 10 ka, the north dried out,
whereas maximum moisture was focused at the mid-latitudes, though the south remained dry. This pattern reflects latitudinal migration of the Southern Westerlies and their associated storm tracks (20). Thus, regional climate proxies suggest that between 45°S and 50°S temperature warmed and precipitation east of the Andes increased throughout the YD, reaching maximum values by 11 ka.

There is evidence for correlative glacier advances at ~11 ka at other locations east of the Andes that indicates that the PB I moraine is not the result of a glacial surge unrelated to climate. Two boulders with exposure ages of 10.5 ± 2.6 ka and 12.2 ± 3.0 ka on a delta 100 m above Lago General Carreras (46°S) are consistent with diversion of the outlet (the Rio Baker) by glaciers advancing eastward from the Northern Patagonian Icefield (NPI) (22). In the Rio Bayo valley, draining the northern NPI, exposure ages of boulders resting on striated bedrock are 11.4 ± 1.8 ka and 10.5 ± 1.6 ka (23). In the Cordilleran foothills north of Lago Argentino, minimum 14C ages of alpine glacier moraines in the Rio Guanaco drainage are provided by rootlets in a channel (10.7 ± 0.2 ka) and peat in a kettle (10.9 ± 0.2 ka) (7). In contrast, on the west side of the Andes at these latitudes, there is neither evidence of a glacial advance (24) nor of climate change in other proxies (25).

The surface exposure age of 10.8 ± 0.5 ka is younger than the mean 14C age of 11.7 ± 0.3 ka from the Brazo Rico outlet channel (Fig. 1C), which indicates that peat was accumulating in the channel before deposition of the PB I moraine boulders. Thus, we infer that, rather than being contemporaneous, the Brazo Rico moraine predates the PB moraines (SOM text).

In summary, multiple independent paleoclimate records suggest that the extensive glacier advance that occurred at Lago Argentino 10.8 ± 0.5 ka on the dry, eastern side of the Andes (50°S) was a response to dramatically increased precipitation rather than dramatic cooling, such as in the North Atlantic region. In this sector of Patagonia, the YD was characterized by increasing easterly sourced precipitation that peaked at ~11 ka with an associated ELA depression of ~550 m. The moisture was likely carried by southeasterly circulation around a lee-side low-pressure trough resulting from the focusing of the Southern Westerlies between 45°S and 50°S. The ACR was a period of aridity and cooler climate in which the ice caps retreated within the Cordillera. This contrasts with the glacial chronology at the Straits of Magellan at 52°S (4) and Lago Buenos Aires at 46°S (16), where glaciers advanced during the ACR.

Combined with similar climate records from New Zealand (8) (Fig. 2B), the Patagonian moraine chronology indicates that in the southern mid-latitudes, glaciers were responding to marked increases in precipitation resulting from changes in the position and intensity of the Southern Westerly circulation, rather than hemispheric cooling during the YD. That accumulation, rather than summer ablation (temperature), dominates the mass balance of these glaciers is probably a consequence of the extremely high accumulation rates and low seasonality as compared with glaciers in more continental climate regimes. Thus, although apparently synchronous climate changes occurred in the southern mid-latitudes during the YD, the glacier advances were not due to worldwide cooling. Rather, these climate changes show a correspondence with trends in Antarctic ice cores wherein glacier advances in the Patagonian steppe (50°S) and New Zealand occurred during peak temperatures in Antarctica rather than during the ACR.

### References and Notes

Electronic Publication and the Narrowing of Science and Scholarship

James A. Evans

Online journals promise to serve more information to more dispersed audiences and are more efficiently searched and recalled. But because they are used differently than print—scientists and scholars tend to search electronically and follow hyperlinks rather than browse or peruse—electronically available journals may portend an ironic change for science. Using a database of 34 million articles, their citations (1945 to 2005), and online availability (1998 to 2005), I show that as more journal issues came online, the articles referenced tended to be more recent, fewer journals and articles were cited, and more of those citations were to fewer journals and articles. The forced browsing of print archives may have stretched scientists and scholars to anchor findings deeply into past and present scholarship. Searching online is more efficient and following hyperlinks quickly puts researchers in touch with prevailing opinion, but this may accelerate consensus and narrow the range of findings and ideas built upon.

Scholarship about “digital libraries” and “information technology” has focused on the superiority of the electronic provision of research. A recent Panel Report from the U.S. President’s Information Technology Advisory Committee (PITAC), “Digital Libraries: Universal Access to Human Knowledge,” captures the tone: “All citizens anywhere anytime can use any Internet-connected digital device to search all of human knowledge…. In this vision, no classroom, group, or person is ever isolated from the world’s greatest knowledge resources” (1, 2). This perspective overlooks the nature of the interface between the user and the information (3). There has been little discussion of browsing/searching technology or its potential effect on science and scholarship.

Recent research into the practice of library usage measures the use of print and electronic resources with surveys, database access logs, circulation records, and reshelving counts. Despite differences in methodology, researchers agree that print use is declining as electronic use increases (4), and that general users prefer online material to print (5). These studies are also in general agreement about the three most common practices used by scientists and scholars who publish. First, most experts browse or briefly scan a small number of core journals in print or online to build awareness of current research (6). After relevant articles are discovered online, these are often printed and perused in depth on paper (7). A second practice is to search by topic in an online article database. In recent years, the percentage of papers read as a result of browsing has dropped and been replaced by the results of online searches, especially for the most productive scientists and scholars (8). Finally, subject experts use hyperlinks in online articles to view referenced or related articles (6). Disciplinary differences exist. For example, biologists prefer to browse online, whereas medical professionals place a premium on purchasing and browsing in print. In sum, researchers peruse in print, browse in print or online (9), and search and follow citations online. These findings follow from the organization and accessibility of print and online papers. Print holdings reside either in a physical “stack” by journal and topic, arranged historically, or in a “recent publications” area. For print journals, the table of contents—its list of titles and authors—serves as the primary index. Online archives allow people to browse within journals, but they also facilitate searching the entire archive of available journals. In online interfaces where searching and browsing are both options (e.g., 3 ProQuest, Ovid, EBSCO, JSTOR, etc.), the searching option (e.g., button) is almost always placed first on the interface because logs demonstrate more frequent usage. When searched as an undifferentiated archive of papers, titles, abstracts, and sometimes the full text can be searched by relevance and by date. Because electronic indexing is richer, experts may still browse in print, but they search online (10).

What is the effect of online availability of journal issues? It is possible that by making more research more available, online searching could conceivably broaden the work cited and lead researchers, as a collective, away from the “core” journals of their fields and to dispersed but individually relevant work. I will show, however, that even as deeper journal back issues became available online, scientists and scholars cited more recent articles; even as more total journals became available online, fewer were cited.

Citation data were drawn from Thompson Scientific’s Science, Social Science, and Arts and Humanities Citation Indexes, the most complete source of citation data available. Citation Index (CI) data currently include articles and associated citations from the 6000 most highly cited journals in the sciences, social sciences, and humanities going back as far as 1945, for a total of over 50 million articles. The CI flags more than 98% of its journals with from 1 to 3 of a possible 300 content codes, such as “condensed matter physics,” “ornithology,” and “inorganic and nuclear chemistry.” Citation patterns were then linked with data tracking the online availability of journals from Information Today, Inc.’s Fulltext Sources Online (FSO).

FSO is the oldest and largest publication about electronic journal availability. Information Today began publishing FSO biannually in 1998, indicating which journals were available in which commercial electronic archives (e.g., Lexis-Nexis, EBSCO, Ovid, etc.) or if they were available freely on their own Web site, and for how many back issues. Merged together by ISSN (International Standard Serial Number), the CI and FSO data allowed me to capture how often articles online availability changes the use of published knowledge in subsequent research. FSO’s source distinction further allows comparison of print access with the different electronic channels through which scientists and scholars obtained articles—whether a privately maintained commercial portal or the open Internet. The combined CI-FSO data set resulted in 26,002,796