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Mountain glacier evolution in the Iberian Peninsula during the Younger Dryas

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A B S T R A C T

We review the evolution of glaciers in the Iberian Mountains during the Younger Dryas (12.9–11.7 ka, following the chronology of Greenland Stadial 1 – GS1) and compare with available environmental and climate data to investigate glacier dynamics during cold stadial episodes. The best examples of Younger Dryas moraines are found in the Central Pyrenees, involving short ice tongues up to 4 km in length in the highest massifs (above 3000 m a.s.l.) of the southern versant. Small cirque glaciers and rock glaciers formed during the YD occurred in other Pyrenean massifs, in the Cantabrian Range and in the Gredos and Guadarrama sierras (Central Range), as indicated by several rocky, polished thresholds that were ice-free at the beginning of the Holocene. Although some former rock glaciers were re-activated during the Younger Dryas, glacial activity was limited in the southernmost part of the Iberian Peninsula (Sierra Nevada).

Most Iberian records show vegetation changes during the YD characterized by a forest decline and an expansion of shrubs (mainly *Juniperus*) and steppe herbs, although the vegetation response was not homogeneous because of variable resilience among ecosystems. Available records also document a variable lake response in terms of hydrology and productivity, with a decrease in sedimentation rates and organic productivity in most high altitude lakes and increases in salinity and relatively lower lake levels at lower altitudes. The impact of the Younger Dryas on the coastal environment was almost negligible, but it was responsible for a brief cessation in sea level rise. High-resolution analyses of new speleothem records have documented a double structure for the YD with an earlier drier phase followed by a relatively more humid period.

The review of geomorphological evidence demonstrates a strong latitudinal control of glacial activity during the YD, with more intense development in the northern than in the southern regions. The increase in humidity during the second phase of the YD in southern latitudes could have been a decisive factor for glacier advance in the northern Iberian mountains.

1. Introduction

Studies of glacier dynamics and environmental changes at the end of the Upper Pleistocene have markedly increased worldwide in recent years, with both contribution from geomorphology and glacier geology and new palaeoenvironmental studies based on proxies in marine and lacustrine sediments (e.g. Dormoy et al., 2009; Fletcher et al., 2010a; González-Sampériz et al., 2010; Clark et al., 2012; Moreno et al., 2014). These have provided high-resolution information on climate fluctuations that occurred prior to and following the Last Global Glacial Maximum (LGM) (GS-2.1b; 21–17.5 ka), and also evidence for the synergetic factors controlling climate changes. Some climate changes during deglaciation occurred abruptly, and they have put forward the need for early warning systems, because similarly rapid changes could occur in the future (e.g. Lenton, 2011).

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The LGM was the period when the Scandinavian, Irish–British and Laurentide ice sheets were at their maximum extent, coinciding with the period of lowest sea level (approximately −130 m relative to the current sea level; Yokoyama et al., 2000). The period between the LGM and the early Holocene is known as a period of deglaciation. Nevertheless, glaciers did not continuously retreat during this period, but rather underwent several major expansions within a general process of retreat. The growth of glaciers during deglaciation occurred in two short periods in which the temperature underwent an accelerated decline. These periods are known as: (i) the traditionally known as Oldest Dryas-OD, between 17.5 and 14.5 ka, more recently named as Greenland Stadial 2.1a (GS-2.1a), and (ii) the Younger Dryas-YD, also known as GS-1, which was a relatively short cold period between approximately 12.9–11.7 ka (Rasmussen et al., 2014). The YD resulted in glacial advances in most mountain areas of the world (Davis et al., 2009), and the ice sheets (e.g. Ballantyne, 2012; Marks, 2015). The OD and YD were separated by a warm period (GI-1, or Bølling-Allerød), which in many mountain areas resulted in both forest expansion (Fletcher et al., 2010a, 2010b; González-Sampériz et al., 2010; Carrión et al., 2010), and the rapid and complete melting of some glaciers, whereas the ice sheets underwent a major retreat coinciding with the recovery of milder climatic conditions in the Northern Hemisphere (14.7–12.9 ka) (Makos et al., 2013a; Rasmussen et al., 2014). The transition in climatic conditions between the Allerød and the YD was extremely abrupt (Brauer et al., 2008; Moreno, 2014), occurring in only a few years. Therefore, this period is a paradigm of abrupt climate change, thus increasing interest in its study in the context of current climatic change. The onset of the YD has been associated with the catastrophic output of glacial meltwater from Agassiz Lake to the Arctic Ocean (Murton et al., 2010). This would have caused reorganization of the North Atlantic atmospheric circulation (Hughen et al., 2000), weakening of the Atlantic Southern Overturning circulation (Broecker, 2006; Benway et al., 2010; Meissner, 2015), and a considerable increase in Arctic sea ice (Cabedo-Sanz et al., 2013). These changes caused a general reduction in temperature (1 °C) throughout the entire Northern Hemisphere (Shakun et al., 2012), although analysis (Buizert et al., 2014) of the Greenland ice sheet showed a reduction of approximately 8 °C compared with the Bølling-Allerød (i.e. 4.5 °C less than during the OD).

An alternative explanation for the abrupt start of the YD is the impact of one or more meteorites in the Laurentian ice sheet, which caused immediate cooling, the extinction of megafauna, and changes in human populations (Firestone et al., 2007). The impact, probably near the Great Lakes, would have liberated sufficient meltwater to interrupt oceanic circulation. Although those proposing this hypothesis have identified several impact markers (including iridium concentrations) at the boundary of the Allerød and the YD, it remains a highly debated and unorthodox hypothesis (Meltzer et al., 2014; van Hoesel et al., 2014). Renssen et al. (2015) noted that simulation of the YD climate signal is better achieved using a combination of processes, including “a weakened Atlantic Meridional Overturning Circulation, moderate negative radiative forcing and an altered atmospheric circulation”. They conclude that the factors that explain abrupt climate changes “are more complex than suggested so far”.

The occurrence of an extremely cold, short duration event immediately prior to the Holocene has been reported for a large variety of European environments, including the front of the Scandinavian ice sheet and a number of European mountain areas. Its duration has recently been established from Greenland ice cores, and it has been defined as a chronostratigraphic unit and termed GS-1 (Greenland Stadial 1; Lowe et al., 2008; Rasmussen et al., 2014); in some cases local names have been used to refer to this well-defined period of glacial advance.

In the Greenland ice sheet the YD cooling did not represent a generalized advance of the ice sheet fronts, although it did occur in some sectors, and the trend to a loss of ice volume persisted (Vasskog et al., 2015). In Gurreholm Dal, in the eastern sector, three morainic ridges are well preserved, the outermost of which is attributable to the YD (Vasskog et al., 2015).

Following a major retreat of the Fennoscandian ice sheet during the Bølling-Allerød, the YD was a period of advance of the ice sheet front, despite a continuous loss of ice mass (Mangerud et al., 2013). This coincided with the last great advance of this ice sheet, leaving two significant sequential morainic ridges (the Salpausselk moraines in Finland and Middle Swedish End Moraine Zone in Sweden) in a cold and dry environment, prior to the definitive retreat (Rinterknecht et al., 2006; Birks et al., 2012; Greenwood et al., 2015; Hughes et al., 2015; Stroeven et al., 2015). This re-advance enabled the fronts of the ice sheet to reach the Estonian and Russian coasts at approximately 13.3 ka (the Pandivere-Neva Stadial), and to Estonia again in 12.7 ka (Palivere Stadial) (Marks, 2015). In Iceland the ice mass re-occupied most of the island between 13.8 and 12.0 ka (Péturson et al., 2015). The British–Irish ice sheet, which had reduced markedly during the Bølling-Allerød, generally advanced, forming numerous moraines in the Scottish Highlands between 12.9 and 11.5 ka during the so-called Loch Lomond Stadial, which is equivalent to the YD (Ballantyne, 2010, 2012; Hughes et al., 2015). The location and dating of these moraines suggest that the maximum ice extent occurred in two different stages at the beginning of the YD, before finally disappearing at the end of the period (Boston et al., 2015).

There have been numerous studies in the Alps related to the Egesen Stadial, the name by which the YD is known in Switzerland. For instance, Hippe et al. (2013) identified a marked retreat of glaciers during the Bølling-Allerød interstadial (Ivy-Ochs et al., 2008); at the beginning of the YD the retreat ceased abruptly and a glacier re-advance commenced, based on dating of a number of morainic complexes. Ivy-Ochs et al. (2008, 2009) noted that the YD was a highly unstable period involving several stages and a progressive reduction of precipitation in at least 50% in the central valleys (Kerschner et al., 2000). In a recent review of deglaciation in the Alps, Ivy-Ochs (2015) noted that most of the Alps were free of ice during the Bølling-Allerød interstadial, whereas the glaciers repeatedly advanced several kilometers from the cirque headwalls during the Egesen Stadial, developing various groups of moraines between 13.5 and 12 ka.

Most of the High Tatra Mountains were also deglaciated during the Bølling-Allerød (Makos et al., 2013a). Glacier expansion during the YD created a main moraine at approximately 12.5 ka (Makos et al., 2013b). Many glaciers disappeared at approximately 11 ka, although some may have remained during the Early Holocene, sheltered in north-facing slope cirques (Makos, 2015). In the Apennines the YD is referred to as Monte Aquila Stadial, and its maximum extent was approximately 10% of that recorded during the LGM. The end moraines were located in some cirques (Grand Sasso, Majella, and Velino) upstream of the cirque threshold (Giraudi, 2015). Evidence of the YD has also been found in mountain massifs of the Anatolian Peninsula in Turkey (Akçar et al., 2007; Zahno et al., 2009, 2010). Similarly, moraines corresponding to glacier advances dated at 11.1 ± 1.4, 12.2 ± 1.5, and 12.4 ± 1.6 ka (Hughes et al., 2011) have been found in the Moroccan High Atlas.

The decline in temperature from the beginning of the YD was pronounced in the European mountains. According to Clark et al. (2012), the cooling ranged from 5 to 10 °C, and ended abruptly with a rapid increase of approximately 4 °C. Makos et al. (2013b) estimated that in the High Tatra Mountains the temperature was 6 °C lower than the current mean annual temperature, which is