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Climate of the Past Discussions

Defining the Little Ice Age

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Abstract

The "Little Ice Age" (LIA) is possibly the best-documented climatic anomaly of the past. A wide range of datasets portrays a harsh climate that worsened living conditions, primarily in terms of cooler temperatures, for people across Europe sometime during the last millennium. Regardless of the vast amount of data covering the LIA, there is presently no consensus concerning its spatial manifestation (was it regional or global?), its temporal constraints (when did it start and end?), or the broad-scale dynamics associated with it (what mechanisms did it involve?), although there is no shortage of suggestions. Based on a new compilation of data reflecting atmospheric circulation at both high and low latitudes, we show that the LIA lasted for roughly 400 years (~1400–1800 AD). During this period at least four major atmospheric circulation systems on Earth co-varied on decadal to centennial timescales: Northern Annular Mode (NAM), Intertropical Convergence Zone (ITCZ), El Nino-Southern Oscillation (ENSO) and West African Monsoon (WAM). This pattern of convergence suggests that a strong coupling between these circulation systems was an important pre-condition for the realisation of the LIA.

1 Introduction

Ask 10 different scientists to define the "Little Ice Age" (LIA) and you are likely to get 10 different answers in terms of climate dynamics, spatial manifestation, and timing. F. E. Matthes initially applied the concept in the late 1930s to describe what appeared to be a period of glacier expansion in North America, arguably starting some few thousands years ago. A few decades later, Porter and Denton (1967) dated glacier fluctuations in Sierra Nevada, the ones originally referred to by Matthes. They effectively constrained the onset of the advances to being roughly 3000–4000 years old and argued that the LIA concept should be "allowed to pass into limbo" and be replaced with the more succinct "Neoglaciation" (cf. Moss, 1951).

But with Hubert Horace Lamb's canonical climate studies published in the 1960s, the LIA concept evolved and rapidly became a climatically defined period, resonating with a wider scientific community that continued using the concept. The timing of the LIA was also limited, occurring in the last millennium – more specifically between AD 1430–1850. This was more in-line with available historical evidence of glacier resurgence in the Swiss and French Alps, as well as in Scandinavia. The efficient combination of reduced insolation and increased volcanic activity became a favoured explanation for glacier expansion and deteriorating climatic conditions (Lamb and Johnson, 1961). Since that time forward, the definition of the LIA has become increasingly muddled and watered down (e.g., Matthews, 2005; Ogilvie and Jonsson, 2001).

The definition of the LIA is still an unresolved issue. Some have argued that the concept should be abandoned unless it specifically concerns glacier fluctuations (Luckman, 2000; Grove, 2001). Given that the LIA is among the most frequently referred to climate anomalies of the past, both within and outside the scientific community, a better definition than what hitherto has been available is warranted. Providing a better definition of the LIA, and hence a better dynamical understanding, is what is at aim here, but let us first elaborate on the general context.

Most environmental proxy-records covering parts or the entire current interglacial (~11 700 years, referred to as the Holocene) suggest that climate alternates on decadal to centennial time scales, not necessarily in defined periods (cf. Bond et al., 2001), but irregularly (Bradley, 1999; Cronin, 1999). Because of the overall changes in forcing during the Holocene, many paleo-records show one or two shifts in mean state separating, for instance, the warming referred to as the Holocene Optimum (9000 to 6000 years BP) from the colder period known as the Neoglaciation (<4000 years BP) (Wanner et al., 2008; Mayewski et al., 2004; Bentley et al., 2009; Mayewski et al., 2009; Paasche and Bakke, 2009).

Although many time-series covering the Holocene are hampered by considerable uncertainty, at least when compared to modern data, shared temporal patterns on decadal to centennial timescales appear to be an intrinsic feature of our interglacial

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climate. Multi-decadal patterns are also documented for the last 100 years in instrumental records, both in air and ocean temperatures. Recently, Chylek et al. (2010) demonstrate, for instance, that Polar areas north and south of 64° show a stringent anti-phase temperature pattern on multi-decadal time scales. This lends support to the idea that such patterns have been common throughout the Holocene.

Seeking out and connecting these patterns in world-wide Holocene records will better enable us to scrutinise the potential impact that natural climate variability may have on future temperature and precipitation trends – either by re-enforcing, weakening, or cancelling them. For this and other reasons, the understanding of natural climate variability on longer timescales needs to be better mapped and understood.

Among the most intriguing – and the most investigated – climate anomalies of the Holocene is the LIA. Major temperature reconstructions describe a Northern Hemisphere cooling of 0.5 to 1 °C that lasted for centuries (Mann et al., 2008; Mann et al., 2009). Although a wide range of archives has documented this cool centennial anomaly, particularly the glacier-based ones (e.g., Grove, 2001), two recurring features suggest that the current understanding of the LIA is incomplete.

The first problem is related to the timing of the event, which often differs by several hundred years. This has resulted in the unfortunate practice of individual researchers tending to define the LIA according to their own choosing. Consequently, in the literature, the LIA lasts from anywhere between 700 to 100 years, and occurs some time between AD 1200–1900. Dating uncertainties and low-resolution records add to the overall temporal uncertainty.

The second problem (or perhaps challenge) is that the current understanding of the LIA is based on multifaceted proxies – such as historical accounts, tree-rings, corals, diatom distributions, ice cores, lake sediments, and moraines – each of which record specific aspects of climate in their individualistic fashion. This "proxy-individuality" occasionally makes it difficult to track and reconstruct a particular climate anomaly in a statistical sense (Rutherford et al., 2005).

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Here the LIA is approached by (i) examining available data on selected glaciers located in the North Atlantic sector (79° N to 45°N), and (ii) compiling and comparing available proxy datasets that reflect various atmospheric circulation patterns. Although the glacier record is of central importance in many discussions dealing with the LIA, we nonetheless posit that a better definition can be obtained by investigating atmospheric changes at the time.

1.1 Data and methods

Six high-resolution proxy records reflecting atmospheric circulation changes are presented in this paper, all of which are previously published. Methods used to produce the individual proxy-records and detailed explanations to the proxy-climate link are found in the following references: (Bakke et al., 2010; Conroy et al., 2008; Haug et al., 2001; Meeker and Mayewski, 2002; Russell and Johnson, 2007; Shanahan et al., 2009). The compilation of glacier records (Fig. 1) is also based on currently available published material, which is listed in the Supplementary Information (SI). The decision on which glaciers to include in the "Little Ice Age" glacier inventory (Table S1) is based on evaluated precision and dating accuracy of the records in question. As the purpose of this compilation is to primarily underscore the previous temporal uncertainty associated with the LIA, not all available records are included. Moreover, because the authors have intimate knowledge about many of the glacier records from Spitsbergen, Norway, Sweden, and Switzerland, it has been easier to evaluate which ones to include from these countries. References to excellent compilations on glacier activity in Alaska, Canada, and the USA during the last millennium are given in the SI as well.

1.2 Results and discussion

In Fig. 2, the timing of individual maximum glacier positions, assumed to reflect the LIA, is compared to a recent summer temperature reconstruction by Kaufman et al. (Kaufman et al., 2009), which covers the northernmost part of the North Atlantic. As evident from Fig. 2, some of the glaciers, such as the Aletschgletscher, had no less than three advances during the LIA. From other sites, previous advances were erased by the latest maximum advance, which, hence, marks the only LIA advance.

Substantial temporal differences associated with the various glacial (re)advances are a prominent feature in this compilation, highlighting the difficulty in using a proxy, and even a specific one, in trying to frame a particular climatic anomaly such as the LIA. However, most reconstructed glaciers in the NH indicate maximum positions between AD 1600 and 1900 (see Fig. 1 and also Supplementary information (SI) for data); there is even well-dated observations from the Southern Hemisphere (SH) that support glacier advances during the time interval of interest (Schaefer et al., 2009).

All other things being equal, the reasons for this observed discrepancy are (i) that each glacier has a unique *response time* being defined by the time it takes for changes in mass balance – positive or negative – to be manifested in frontal movements (if at all), and (ii) that such changes are driven by shifts in summer temperature as well as winter precipitation, and not just by one of them. Because of these physical constraints, glaciers will necessarily tend to deviate from one another in terms of when they are advancing, and only by isolating the importance of the different aforementioned components is it meaningful to compare the various records – a task not easily accomplished. Results from recent glacier mass balance reconstructions from Canada (Luckman, 2000; Watson and Luckman, 2004), Sweden (Linderholm et al., 2007), Norway (Nesje and Dahl, 2003), and the Alps (Vincent et al., 2005) underscore precisely the importance of being able to distinguishing the respective roles of summer temperatures versus winter precipitation when it comes to understanding the climate change forcing potential LIA-advances.

It can be equally challenging to define the LIA by analysing the various temperature reconstructions existing for the Northern Hemisphere (Mann et al., 2008; Osborn and Briffa, 2006), not only because they, during certain periods, deviate notably from one another (Jansen et al., 2007), but also because it is truly difficult to delimit this period in the individual records. More compelling and recent results indicate that the coldest temperatures during the last millennium took place between 1400 and 1700 C.E. (Mann et al., 2009).

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The combined effect of these two well-known, but partly unanswered, problems constrain our understanding of the LIA, the dynamical implications associated with it, as well as its spatial manifestation. For example, there is currently no consensus whether the LIA was regional or global in scope (e.g., Bradley and Jones, 1993).

In sum this begs the question: When exactly was the LIA? And, how accurately can it be defined in terms of broad-scale climate dynamics?

Answering these questions will not only define the LIA as a climatic anomaly, but it will also further our knowledge about the spectrum of natural climate variability that can be expected from an interglacial climate such as our own. In order to address this challenge, we have compiled state-of-the-art proxy time-series, all of multi-decadal resolution or higher, that specifically reflect atmospheric circulation changes during the last 1400 years. The records are shown in Fig. 3 and include a new glacier reconstruction from northern Norway (Bakke et al., 2010), the compilation of several ice-core records from the Greenland Ice Sheet (Meeker and Mayewski, 2002), a marine core from the Cariaco Basin (Haug et al., 2001), and lake sediment cores from West Africa (Russell and Johnson, 2007), East Africa (Shanahan et al., 2009), and the Galapagos Archipelago in the Pacific Ocean (Conroy et al., 2008).

A shared feature in all of the records is that a major shift started ~1400 AD and terminated 400 years later, at ~1800 AD. This interpretation is based on a qualitative evaluation of the presented data. We posit, nonetheless, that this time interval (1400–1800 AD) delimits the LIA, and that it is possible to explain this near-synchronous shift in terms of changes in broad-scale climate dynamics.

The Norwegian and Greenland records imply that the Northern Hemisphere Annular Mode (NAM) went into a quasi-permanent state of high polarity (negative). The Cariaco record indicates a prevailing southern migration of the Inter Tropical Convergence Zone (ITCZ). The East African and Galapagos records indicate substantial changes in the El Niño/Southern Oscillation (ENSO), whereas the West African record mirrors changes in the West African Monsoon (WAM), which is linked to both the ITCZ and to ENSO.

Not only does this suggest that the atmosphere plays a key role in terms of explaining the dynamics involved in realising the LIA, but it also hints at a seasonal bias in favour of the Northern hemisphere winter. The fact that several of Earth's major atmospheric circulation patterns are involved (cf. Mann et al., 2009) implies a global scope associated with the LIA and perhaps, equally important, suggests that the coupling between these systems was stronger during this time interval than is revealed by modern data.

Increased latitudinal sea surface temperature gradients could arguably intensify the Hadley-cells (Rind, 1998), which would tend to steepen the equator to pole gradient and subsequently enhance the atmospheric connection between the tropics and the extra-tropics (Hendy et al., 2002). In theory, such a scenario should affect both hemispheres. A atmospheric bi-polar link during the LIA is also advocated by Kreutz et al. (1997) who studied ice cores from Greenland and Antarctica (Byrd). Moreover, they argued that the atmospheric circulation system that prevailed during the LIA lasted until present, which conflicts with our observations.

Whether or not the LIA was driven by internal variability only or by additional changes in external forcing is for future work to resolve, but certain points can be raised here. Greenhouse gasses (CO_2 and CH_4) dropped around AD 1400 and remained low until AD 1800 (Siegenthaler et al., 2005; Meure et al., 2006), altering the radiative balance. Coincidentally, there were three historically solar minima during the LIA: Spörer (AD 1450–1550), Maunder (AD 1645–1715), and Dalton (AD 1790–1820), which in sum make up almost 200 years in total for AD 1400–1800. This suggest a weak, but significant change, in solar forcing (Bard et al., 2000). Apparently, even modest changes in solar activity impact the organisation of the troposphere and the stratosphere (Rind et al., 2008).

It has, for instance, been demonstrated that reduced solar activity during the Maunder Minimum might push the NAM, transmuted by a stratospheric response, into a state of negative polarity (Shindell et al., 2001). Several large volcanic eruptions, which had a notable impact on the climate, occurred during the same time interval (Robertson et al., 2001). One of the atmospheric implications of volcanic eruptions, besides a cooling effect, is that they tend to weaken the westerlies in the following 5–7 years (Shindell et

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al., 2003), i.e. eruptions could potentially amplify an already existing negative trend in the NAM.

Finally, it should be noted that Lund and colleagues argue that a 20% reduction (compared to modern values) in the northward heat transport of the Gulf Stream occurred from AD 1400 to 1800 (Lund et al., 2006). It is speculated that this weakening of the North Atlantic subtropical gyre followed from a southward ITCZ migration; this argument is in line with data from the Cariaco basin, as well as the initial interpretation (Haug et al., 2001). Sachs et al. (2009) also confirm a southward shift of the ITCZ during the LIA – in the order of 5° – and suggest that it might be triggered by a reduction in the radiative forcing at the surface of only ∼0.75 $W m^{-2}$.

The shifts observed in the proxy-records presented here (Fig. 3) strongly suggest that the atmosphere is pivotal for understanding the dynamical changes associated with the LIA and that the major circulation pattern(s) fluctuate on century-time scales during interglacial climate conditions. When comparing this pattern with how NH-glaciers responded, it becomes evident that the glaciers needed the first 100–200 years of the LIA to grow and expand, and that it was not until ca. AD 1600 that many of the glaciers reached maximum positions (Fig. 2). Likewise, it explains why so many glaciers in the North Atlantic sector remained large until AD ∼1900. The effect of individual response time combined with the time used on the build-up phase illustrates the difficulties associated with using glaciers to delimit the LIA. As we have shown here, the atmosphere is better suited for that task.

Whether a sustained and regional cooling prevailing for centuries is a necessary pre-condition for a stronger coupling between the atmospheric modes, in response to relatively modest changes in the radiative forcing, remains to be seen.

2 Conclusions

A concise definition of the climate anomaly known as the "Little Ice Age" is provided by this study. It suggests that the period was initiated by a major shift in several of

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the most important atmospheric circulation patterns on Earth, including the Northern Annular Mode (NAM), the Intertropical Convergence Zone (ITCZ), the West African Monsoon (WAM), and the El Nino–Southern Oscillation (ENSO). The trends start to converge around AD 1400, which coincidentally coincides with a period of reduced solar activity. A similar shift in the abovementioned circulation patterns also marks the end of the "Little Ice Age", occurring circa AD 1800. The data included in this study indicate that the LIA was a global phenomenon, but the paucity of data from the Southern Hemisphere still makes it difficult to assess the actual spatial extent.

The majority of glaciers located in the North Atlantic sector advanced at least one time during this interval, but when compiled and compared to summer temperature reconstructions, it becomes clear that glaciers are not well-suited for defining a period such as the LIA unless the physics governing individual advances are understood in some detail. The mechanisms that facilitated and instigated the LIA are still not settled, but we observe a pattern that strongly suggests that, at times, the major atmospheric systems on Earth are more connected than at present for reasons we do not fully understand.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/6/2159/2010/cpd-6-2159-2010-supplement.pdf.

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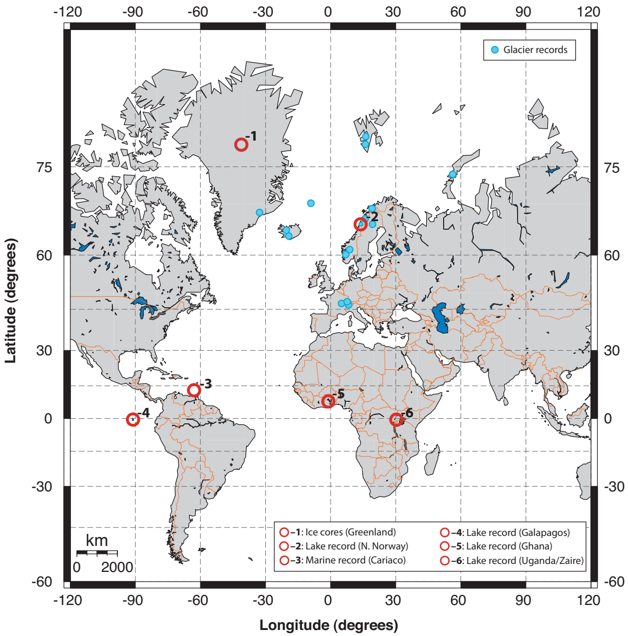

Fig. 1. Overview map of LIA glacier sites (blue dots) compiled and examined in this study (Fig. 2), as well as proxy-records indicating changing atmospheric circulation patterns (Fig. 3).

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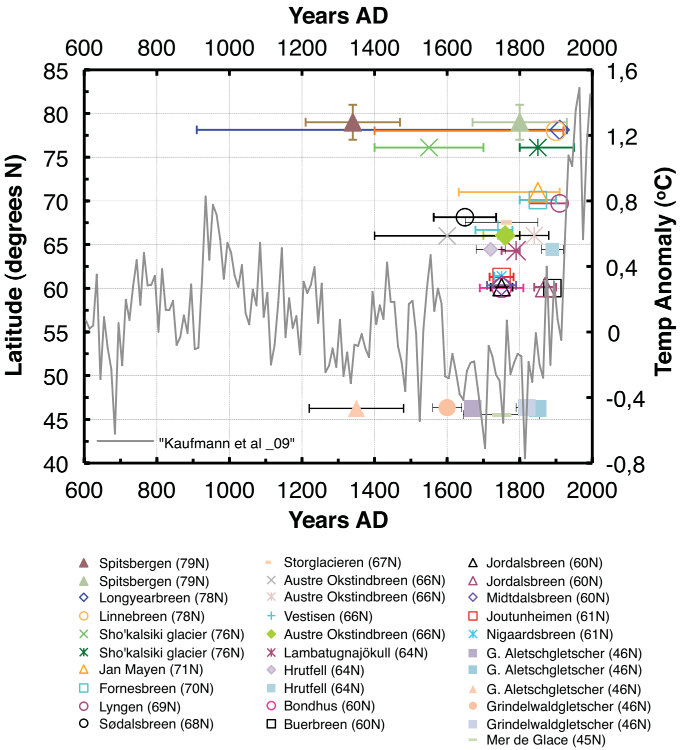

Fig. 2. Glacier advances in the North Atlantic sector (79–45° N) associated with the LIA shown in relation to changes in summer temperature in the Northern Hemisphere (Mann et al., 2008) during the last 1400 years (right y-axis). Error bars, associated with glacier LIA-positions, are assigned based on approximate dating uncertainties (see Table S1). As evident from the figure, there is a weak relationship between cool summer temperatures and glacier advances, but not a one-to-one relationship. Nevertheless, most glacier advances occurred between ca. 1600 AD and 1900 AD.

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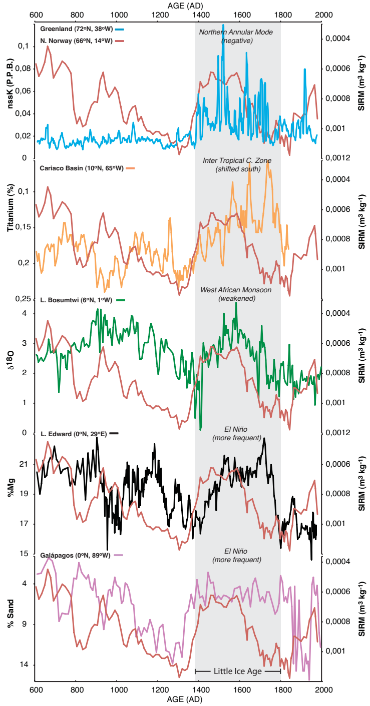

Fig. 3. The six high-resolution proxy records listed in the figure reflect changes in atmospheric circulation patterns from the Arctic (top) to the Tropics (bottom), covering the last 1400 years. The new glacier reconstruction (red curve, second y-axis, reversed values) from northern Norway (Bakke et al., 2010), suggested to be sensitive to changes in the NAM, is represented by Saturation Isothermal Remanent Magnetization (SIRM), which is a magnetic property reflecting the glacier size. According to the proxies shown here, the LIA lasted from ca. 1400 to 1800 AD (emphasised by the grey bar) and marks a defined period, which most likely was a global event. A full description of the individual methods and interpretations are given in the relevant references: Greenland (Meeker and Mayewski, 2002), N. Norway (Bakke et al., 2010), Cariaco basin (Haug et al., 2001), Lake Bosumtwi (West Africa) (Shanahan et al., 2009), Lake Edward (East Africa) (Russell and Johnson, 2007), and Galapagos (Conroy et al., 2008).