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*The term Little Ice Age was originally coined by F Matthes in 1939 to describe the most recent 4000 year climatic interval (the Late Holocene) associated with a particularly dramatic series of mountain glacier advances and retreats, analogous to, though considerably more moderate than, the Pleistocene glacial fluctuations. This relatively prolonged period has now become known as the Neoglacial period. The term Little Ice Age is, instead, reserved for the most extensive recent period of mountain glacier expansion and is conventionally defined as the 16th–mid 19th century period during which European climate was most strongly impacted. This period begins with a trend towards enhanced glacial conditions in Europe following the warmer conditions of the so-called medieval warm period or medieval climatic optimum of Europe (*see ***Medieval Climatic Optimum****, Volume 1), and terminates with the dramatic retreat of these glaciers during the 20th century. While there is evidence that many other regions outside Europe exhibited periods of cooler conditions, expanded glaciation, and significantly altered climate conditions, the timing and nature of these variations are highly variable from region to region, and the notion of the Little Ice Age as a globally synchronous cold period has all but been dismissed (Bradley and Jones, 1993; Mann* et al.*, 1999). If defined as a large-scale event, the Little Ice Age must instead be considered a time of modest cooling of the Northern Hemisphere, with temperatures dropping by about 0.6 °C during the 15th–19th centuries (Bradley and Jones, 1993; Jones* et al.*, 1998; Mann* et al.*, 1998, 1999).*

Documentary accounts of dramatic mountain glacier retreats and advances during past centuries, widespread historical documentation of weather conditions (e.g., Pfister, 1995, 1998) and even a handful of several centuries-long thermometer measurements (e.g., Bradley and Jones, 1993) provide incontrovertible evidence of the occurrence of the Little Ice Age in Europe and other regions neighboring the North Atlantic during the 16th–19th centuries. This climatic era has, in fact, been pictorially captured in paintings detailing the greatly expanded range of various mountain glaciers in the French and Swiss Alps during past centuries. The juxtaposition of such early artists' renderings of such glaciers against their modern photographic counterparts, provides a particularly graphic illustration of the dramatic climatic changes associated with the Little Ice Age in Europe (Figure 1).

These dramatic glacial advances often had important practical consequences for nearby human populations. In the Chamonix valley near Mont Blanc, France, numerous farms and villages were lost to the advancing front of a nearby mountain glacier. The damage was so threatening that the villagers summoned the Bishop of Geneva to perform an exorcism of the dark forces presumed responsible (this procedure, as for most human attempts at weather modification, does not appear to have been successful). Such societal threats were common during the late 17th and early 18th centuries, as many glaciers expanded well beyond their previous historical limits. Colder conditions combined with altered patterns of atmospheric circulation, appear to be tied to the prevalent crop failures in the more northern areas of Europe of the time. There are widespread reports of famine, disease, and increased child mortality in Europe during the 17th–19th century that are probably related, at least in part, to colder temperatures and altered weather conditions. Certainly, not all consequences of the associated climate changes were deleterious for European society. In London, the freezing of the Thames River, commonplace during the era, was celebrated with a winter carnival. The colder climate, furthermore, appears to have served as inspiration for writers of the time. The greater frequency of cold, icy winters sentimentally framed author Charles Dickens' notion of the old-fashioned white Christmas. The unusually cold summer of 1816 (the year without a summer – see discussion herein) forced Mary Shelley to spend her summer vacation at Lake Geneva indoors, where she and her husband entertained each other with horror stories, one of which resulted in her writing the novel *Frankenstein* (see Le Roy Ladurie, 1971).

The Little Ice Age may have been more significant in terms of increased variability of the climate, rather than changes in the average climate itself. The most dramatic climate extremes were less associated with prolonged multiyear periods of cold than with year to year temperature changes, or even particularly prominent individual cold spells, and these events were often quite specific to particular seasons. In Switzerland, for example, the first particularly cold winters appear to have begun in the 1550s, with cold springs beginning around 1568: the year 1573 had the first unusually cold summer (Pfister, 1995). The increased variability of the climate may have led to alternations between unusually cold winters and relatively warm summers. A severe winter preceded the hot summer that precipitated the Great Fire of London in 1666. A harsh winter followed by a warm summer may have added to the discontent of peasants who stormed the Bastille in Paris during the summer of 1789.

The cooling of the Little Ice Age has frequently been blamed for the demise of Norse settlements in Greenland that had been established during the early centuries of the second millennium. This premise appears, however,

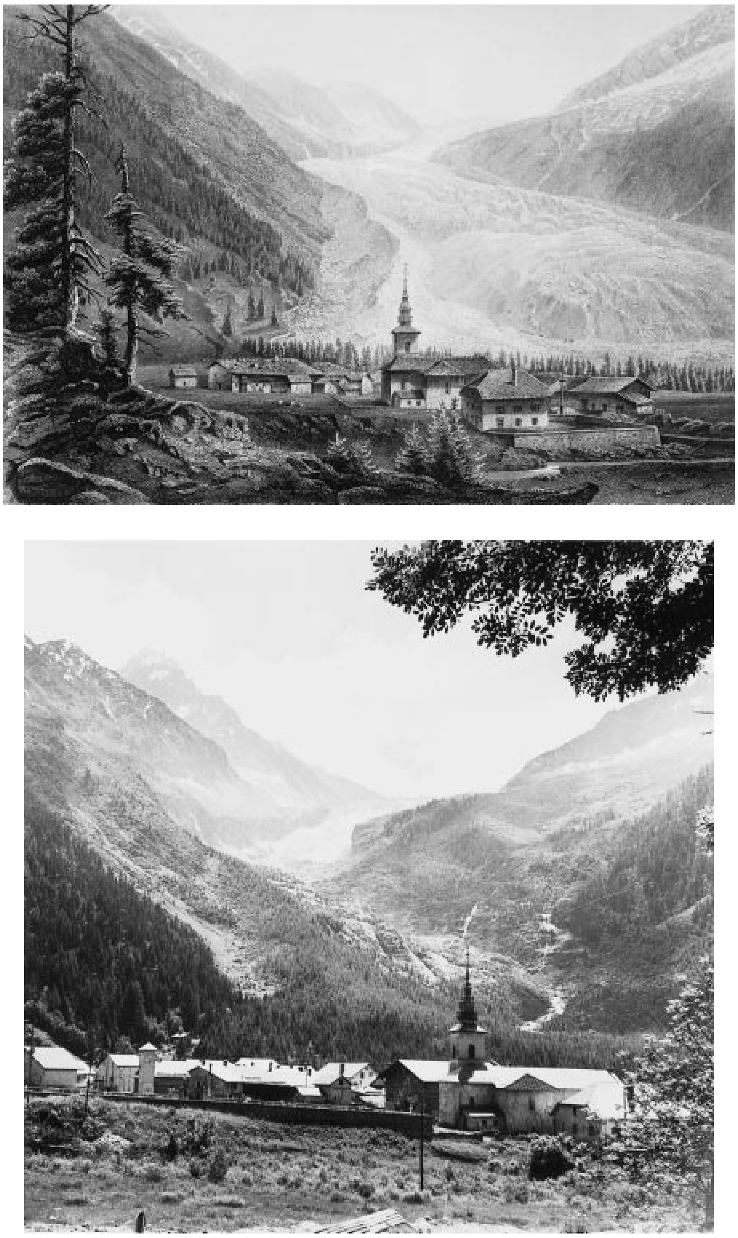

Figure 1 A portrait of the Argentiere glacier in the French Alps from an etching made between 1850 and 1860 just prior to its dramatic withdrawal, and a modern photograph of the glacier from a similar vantage point taken in 1966. (Reproduced by permission of Doubleday and Company, Inc., from Le Roy Ladurie, E, 1971 (Plates XXI and XXII))

to have only limited validity. Expanded sea ice extent in the North Atlantic certainly created problems for fishermen in Iceland and Scandinavia, and for the Norse settlements in Iceland and Greenland. Increased winter sea-ice cover closed off previously accessible trade routes between Scandinavia and Greenland during the late 14th century, cutting off trade with mainland Europe, upon which the Norse settlements relied. The collapse of Norse colonies in Greenland, however, represented a complex reaction to changing climate conditions (including seasonal precipitation/snowfall as well as temperature patterns), and their interaction with societal dynamics, and cannot be understood simply in terms of a lowering of temperatures in the region. In fact, as discussed below, temperature variations in western Greenland in past centuries bear only a limited resemblance to those in Europe, which conventionally have best defined the Little Ice Age.

Outside of the North Atlantic region, the large-scale signature of the Little Ice Age becomes even less clear. Unlike the true ice ages of the Pleistocene, which were marked by a clear global expression associated with dramatic growth of all the major continental ice sheets and a substantial lowering of global temperatures (probably 2–3 °C below current levels), the available evidence does not support the existence of a continuous period of cooler global temperatures synchronous with cold conditions in Europe. What evidence is available suggests, instead, generally colder conditions anywhere from the 13th through 19th century, quite variable in timing from region to region, and in most cases punctuated with intermittent periods of warmth (see Bradley and Jones, 1993; Pfister, 1995). Direct indications of climate variability (e.g., long thermometer measurements or reliable historical documentary records) are rarely available outside Europe and neighboring regions. There are some long instrumental climate records in North America dating back to the mid 18th century and historical information exists in the form of documentary evidence from parts of Canada and the northeastern US from early European settlers, and anecdotal reports from Native Americans in western North America. Such evidence gives a mixed picture of the Little Ice Age in North America. For example, the 17th century, the coldest century in Europe, does not appear to have been unusually cold in North America. By contrast, during the 19th century, as Europe was recovering from Little Ice Age conditions, North America was experiencing some of its coldest temperatures. There are reports, for example, that New York harbor froze over during this period of time. There is also some long-term human documentary evidence of climate changes in Russia and China that provide yet a different picture of temperature variations in past centuries from that of Europe (see Bradley and Jones, 1993 and references therein).

There is geological information from the position of moraines or till left behind by receding glaciers that provide a more global, albeit indirect, picture of the advances (and, less precisely, the retreats) of mountain glaciers. Such evidence suggests, for example, increased glaciation in certain regions of the world outside Europe prior to the 20th century, including Alaska in North America, and New Zealand and Patagonia in the Southern Hemisphere (see Grove, 1988). However, the precise timing of glacial advances in these regions (and even between the western and eastern Alps) differs considerably from region to region, suggesting the possibility that they represent roughly coincident, but independent regional climate changes, rather than globally synchronous increased glaciation. Owing to the complex balance between local changes in melting and ice accumulation, and the effects of topography, all of which influence mountain glacier extent, it is difficult to ascertain the true nature of climate change simply from evidence of retreat of mountain glaciers alone. For example, both increased winter precipitation (through greater accumulation) and lower summer temperatures (through decreased melting or ablation) can lead to increases in glacial mass. Furthermore, the inertia of large glaciers dictates that they respond relatively slowly, and with delays of decades to centuries, in response to any contemporaneous climate changes.

Other information is thus necessary to assess the global-scale climate variations of past centuries. A variety of other types of information is fortunately available to help provide a truly global-scale picture of climate change during past centuries (Bradley and Jones, 1993). These types include a few long-term historical documentary records (particularly outside Europe), supplemented by proxy climate records such as growth and density measurements from tree rings, laminated sediment cores, annually resolved ice cores, isotopic indicators from corals, and long-term ground temperature trends from borehole data. While these indirect measurements of climate change vary considerably in their reliability as indicators of long-term temperatures (varying in the degree of influence by non-climatic effects, the seasonal nature of the climate information recorded, and the extent to which the records have been verified by comparison with independent data), they are, nonetheless, essential for documenting global-scale patterns of temperature change in past centuries.

Comparing temperature estimates over the Northern Hemisphere and globe during past centuries from these different sources provides considerable insight into the regional variability and extent of the Little Ice Age (Figure 2). Slightly preceding the increased growth of mountain glaciers across Europe during the 17th–19th centuries is evidence of a depression of temperatures in the region (Central England – panel e) relative to modern levels by approximately 0.4 °C during the period 1500–1800 and by more than 0.6 °C during the 17th century period of peak cold. The conclusion that the region exhibited its coldest conditions during the 17th century, and began warming significantly during the 19th century, is independently confirmed from tree ring reconstructions of European summer temperatures (see Jones *et al.*, 1998). A Little Ice Age is not as plainly evident in temperature estimates for Western Greenland (panel d), reinforcing the notion that the collapse of Norse civilization in Greenland was not simply a response to cooling temperatures. Temperature trends in Scandinavia (panel f) show some similarities with both those of Greenland and central England, further emphasizing the importance of regional variation in temperature trends over the past few centuries even in the North Atlantic and neighboring regions. In fact, the Little Ice Age appears to have been most clearly expressed in the North Atlantic region in terms of altered patterns of polar atmospheric circulation. Such altered patterns of circulation likely impacted seasonal snowfall patterns in a way that the Norse could not easily adapt to, and may explain differences between temperature variations in Europe and those in Iceland and Greenland. For example, the winter of 1833/1834, an unusually warm winter in central Europe,

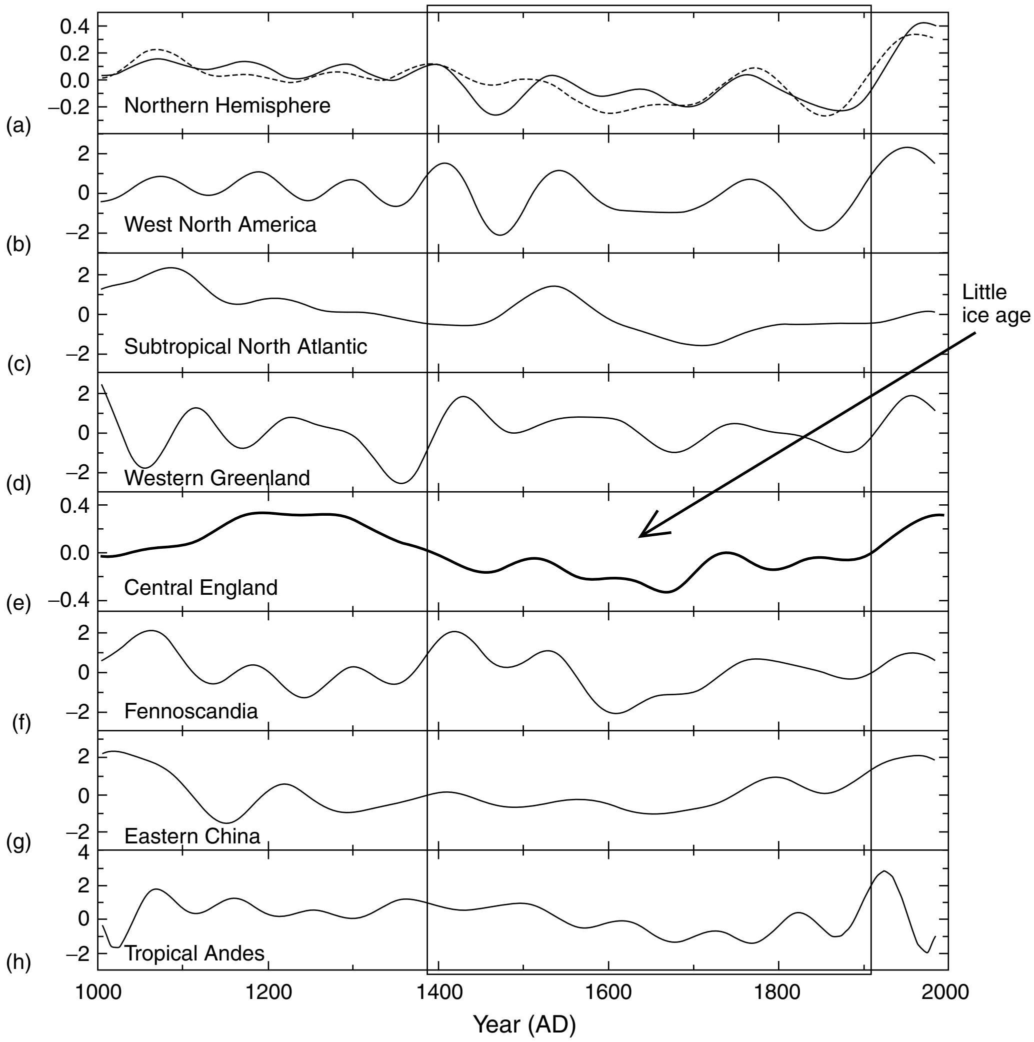

Figure 2 Estimated relative temperature variations during the past millennium for different regions. The records have been smoothed to emphasize century and longer-term variations. (a) Northern Hemisphere mean temperatures as estimated for the annual mean over the entire hemisphere (solid – Mann *et al.*, 1998, 1999) and over the extratropical region during the warm season (dashed – Jones *et al.*, 1998) based on global databases of proxy climate indicators, (b) tree ring data from western North America, (c) sediment record from the Sargasso Sea of the tropical North Atlantic, (d) ice cores from western Greenland, (e) a combination of thermometer, historical and proxy data records from central England, (f) tree ring data from Fennoscandia, (g) phenological evidence from eastern China and (h) ice core data from the tropical Andes of South America. Temperature scale is in °C for (a) and (e), and indicates relative temperature variations otherwise. Panel (e), which best defines the European Little Ice Age, is highlighted, with the large rectangle (extending from about AD 1400 to 1900) indicating more broadly the consensus among regions of the coldest period

appears to have been associated with dramatic changes in storm tracks over Europe, consistent with colder than normal conditions evident in Iceland that same year. While the 17th century appears to represent the timing of peak cooling in Europe, the 19th century was more clearly the period of peak cold in North America (panel b). In both the subtropical North Atlantic (panel c) and the tropical Andes of South America (panel h), peak cooling is evident during the 17th and 18th centuries. Even farther a field in eastern China (panel g), there is less evidence of any distinct cold period during the latter centuries of the millennium, with temperatures rather relatively uniformly depressed from about AD 1100–1800.

Some of the regional variability evident during the Little Ice Age can be understood in terms of changes in atmospheric circulation patterns. Such patterns, particularly the North Atlantic Oscillation (*see* **North Atlantic Oscillation**, Volume 1) – the dominant mode of atmospheric circulation variation in the North Atlantic and neighboring regions – have a particularly strong influence on winter temperatures in Europe. While the coldest year overall in Europe, 1838, was indeed one of the coldest over much of the Northern Hemisphere (the late 1830s were generally quite cold, perhaps due to the effects of the large volcanic eruption in Coseguina, Nicaragua during 1835 – see discussion herein), conditions were, nonetheless, relatively mild over significant portions of Greenland and Alaska. In fact, unusually cold, dry winters in central Europe (e.g., 1–2 °C below normal during the late 17th century) appear to have been associated with the flow of continental air from the northeast towards western Russia and Europe, conditions which, along with warmer than normal temperatures in Greenland and other regions, are consistent with the positive phase of the North Atlantic Oscillation. Warmer than normal winters in Europe, and cooler than normal temperatures in Greenland, tend to arise during the opposite phase.

While the peak maximum cooling occurred at quite different times throughout the Northern Hemisphere, an overall pattern does emerge when one composites regional variations into an estimate of large-scale mean temperature changes (see Mann *et al.*, 1998, 1999; Jones *et al.*, 1998). For the Northern Hemisphere on the whole (both annual mean and extratropical summer – see Figure 2, panel a), the period 1400–1900 appears to have been moderately cooler (approximately 0.3 °C) than the earlier period AD 1000–1400 and about 0.8 °C colder than the late 20th century. Following the cold late 15th century, the 17th and 19th centuries appear as the coldest centuries within this period (although, as discussed above, the spatial pattern of this cooling is quite distinct for the two periods). If one wishes to define the Little Ice Age proper as a time of large-scale cooling, it must be defined as a period of only moderately cooler Northern Hemisphere temperatures from about 1400–1900 (see Figure 2), preceding the rapid warming of the 20th century. For the Southern Hemisphere, evidence for a comparable Little Ice Age is far more diffuse (e.g., Jones *et al.*, 1998).

The existence of the Little Ice Age (whether defined by the particularly cold conditions in Europe during the 16th–18th centuries, or the more modest large-scale cooling of the 15th–19th centuries) invites questions as to what factors may have led to such a cooling.

This unusual period in climate history occurred before the likely influence of human activity (e.g,. the burning of fossil fuels associated with the industrial revolution). Though some of the long-term cooling of the climate prior to the 20th century might have been associated with astronomical factors, such factors cannot explain the pronounced and relatively short-duration cooling observed in many regions.

The explanation for the Little Ice Age must thus lie in other natural causes, whether associated with external forces, or internal noise in the climate system. The injection of sunlight-reflecting sulfate aerosols by explosive volcanic eruptions, for example, may be responsible for some of the cooling of the early and mid 19th century, in particular (see Lean *et al.*, 1995; Mann *et al.*, 1998). A prominent example is the 1815 eruption of Tambora in Indonesia that is typically blamed for the year without a summer. While parts of eastern North America and Europe experienced notable cooling, the observation that other regions, including the western US and the Middle East, appear, in fact, to have been warmer than usual is consistent with a hypothesized relationship between volcanic forcing of climate and the response of the North Atlantic Oscillation. The longer-term variations, and in particular cooler temperatures during the 17th century and warmer temperatures during the 18th century were likely to have been related to a concomitant increase in solar output by the Sun by approximately 0.25% following the Maunder Minimum of the 17th century (Lean *et al.*, 1995; Mann *et al.*, 1998) (*see* **Maunder Minimum**, Volume 1). Finally, changes in the ocean circulation (e.g., the Gulf Stream) of the North Atlantic, and associated impacts on North Atlantic storm tracks, may have emphasized temperature changes in Europe. The relative influences of these various external and internal factors on climate change during past centuries are an area of active climate research.

See also: **Ground Temperature**, Volume 1.

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