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Past global changes and their significance for the future

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Abstract

Placing the short instrumental record of climate into a longer-term perspective provides valuable insights into the envelope of climate variability on timescales of significance to society today. Numerous paleotemperature records reveal that the 20th century has been exceptionally warm in the context of the last millennium, and perhaps many millennia. Furthermore, the coldest decades of the last century (the nadir of the "Little Ice Age") were among the coldest times in the late Holocene. Thus, the world has experienced both the warmest and the coldest extremes of the late Holocene within a brief interval of less than 200 years. Extending the climate record back in time enables the underlying forcing factors (prior to global-scale anthropogenic effects on the climate system) to be identified. Paleoclimatic data are essential to obtain a comprehensive understanding of the climate system, without which reliable forecasting of future conditions will not be possible.

1. Introduction

The overall goal of the International Geosphere Biosphere Programme (IGBP) is: *"To describe and understand the interactive physical, chemical and biological processes that regulate the total earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions ....".* The key interactions and significant changes that are of primary interest are those that occur on timescales of decades to centuries, that affect the biosphere, that are most susceptible to human perturbations, and that (most likely) will lead to a practical predictive capability. These objectives are of course driven by concerns over the ever-increasing impact of human activities on the climate system, *sensu lato*. However, whatever anthropogenic effects there are on climate in the future, they will be superimposed on the underlying background of "natural" climate variability which varies on all timescales in response to different forcing factors. Paleoclimatic research provides the essential perspective on climate system variability, its relationship to forcing mechanisms and to feedbacks that may amplify or reduce the direct consequences of particular forcings. Such a perspective cannot be provided by the very limited set of instrumental data at our disposal and we must therefore examine records of the past in order to comprehend the full range of natural variability and provide confidence in our ability to predict future global changes. Here I present a few examples to illustrate these points, focusing on paleotemperature records from the late Holocene. Elsewhere in this volume, the value of a much longer paleoclimatic perspective is demonstrated, and the importance of paleorecords of various forcing factors is also illustrated (Zielinski, 1999; Beer et al., 1999).

2. An essential perspective

Although a few instrumental meteorological measurements extend back into the 17th century, no extensive network of data exists prior to the mid-19th century. Hence, although we may have a 300 year record of climate at a few specific locations, we have only a ~ 150 year perspective on the spatio-temporal variability of the earth's climate system as a whole. Unfortunately, the period for which we have detailed instrumental records happens to coincide with the time when human activities have increasingly contaminated the atmosphere on a global scale. If we want to understand the relationship between any underlying "natural forcing" and climate variability we must probe further back in time, and for this we must rely on paleoclimate archives (climate proxies). Some archives also contain records related to forcing factors, such as non-sea salt sulfate, or ^{10}Be in

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ice cores (indicative of explosive volcanic eruptions and solar irradiance variations, respectively) enabling a direct chronological comparison between the forcing and the response recorded in the climate proxy record (e.g. Beer et al., 1994; Stuiver et al., 1995).

Teleconnections within the climate system enable certain large-scale variations (e.g. changes in global or hemispheric mean temperature) to be represented by a relatively small number of records, providing they are located in the "right" locations. Of course, *a priori*, we do not know what those locations are, and indeed they may vary over time as boundary conditions change. Bradley and Jones (1993) calculated decadal mean northern hemisphere summer temperature by simply averaging together a set of selected records from three areas — North America, Europe and East Asia. Although the selection of records represented was somewhat arbitrary, it was demonstrated that they closely approximated temperature changes recorded over the last 100 years by a much larger set of instrumental records. This provides a measure of confidence that variations of temperature over longer periods of time at the small set of sites with paleodata do represent changes in the hemispheric mean (C.F. Bradley, 1996). However, to reconstruct the spatio-temporal variability of the climate system (i.e. its geographical pattern of anomalies over time) a more geographically extensive (though not necessarily very dense) network of data is required, in order to capture the many overlapping responses of the climate system to forcing, both external and internal. Mann et al. (1998) used over 50 well-distributed paleoclimatic records (some representing regional networks of additional records) to reconstruct paleotemperature over the past ~ 600 years. The paleoclimatic proxies were calibrated in terms of the main modes of temperature variations (eigenvectors) represented in the instrumental records. Variations across the network of proxies for the period before instrumental records were then used to reconstruct how the main temperature patterns varied over time (i.e. their principal components) and by combining these patterns, large regional, hemispheric or global mean temperature changes, as well as their spatial patterns over time could be reconstructed. To accurately reproduce the *spatial* pattern requires that the proxy data network is extensive enough to capture many of the principal eigenvector patterns. With the data available to Mann et al. (1998) regional patterns of temperature variation could only be meaningfully reconstructed for ~ 250 years, although the large-scale (hemispheric) mean temperature could be reconstructed back to A.D. 1400. This was possible because the proxy data network, even at its sparsest, exhibits a coherent response to variability at the largest scale. In fact, Mann et al. (1999a) have now shown that an even more limited network of data captures enough variance to allow a reconstruction of hemispheric mean temperature back 1000 years, albeit with ever-increasing uncertainty (i.e. expanding confidence limits) the further back in time one goes (Fig. 1).

What do these reconstructions reveal about past temperature variations? When placed in a longer-term perspective, northern hemisphere mean temperature in the 20th century is unique, both in its overall mean and in the rate of temperature increase. In particular, the 1990s have been exceptionally warm, with 1998 exceeding all annual temperatures for at least 1000 years (even taking the estimated uncertainties of earlier years into account). The last 50 years have been the warmest period by far (Table 1). Also apparent is the cold 19th century — the coldest century of the millennium and $\sim 0.28°C$ colder than the 20th century mean (Table 1). Finally, there is evidence for mild episodes, lasting a few decades in the 11th and 12th centuries though the mean temperature was not comparable with the late 20th century levels. All of these conclusions are, of course, subject to the considerable uncertainties posed by an increasingly limited data set as one pushes the reconstruction back in time. Further expansion of the proxy data network will help to refine these conclusions, but it is very unlikely to alter the fact that the climate of the 20th century has been quite exceptional in the context of the last millennium (cf. Pollack et al., 1998)

The temperature reconstruction reveals three characteristic timescales of variability: a long-term cooling trend, from A.D. 1000 to 1900 that may be related to orbital effects and/or to a reduction in solar irradiance. Orbital effects have led to a decline in July radiation over the millennium, especially at mid to high northern latitudes ($\sim 4\ W\ m^{-2}$, outside the atmosphere), though January insolation increased slightly over most of the globe (by up to $\sim 2\ W\ m^{-2}$) (Fig. 2). The radiation gradient from 30 to 60°N in July has also increased by $\sim 3\%$ over the millennium (which favors a slight equatorward displacement of the sub-tropical high pressure centers). In addition, ^{10}Be levels in polar ice (a proxy for solar activity changes) show that irradiance levels were relatively high from $\sim$ A.D.1100 to 1300 (Fig. 3). Together, the higher summer insolation and the higher level of total irradiance earlier this millenium may have caused northern hemisphere temperatures to be warmer at that time, and to slowly decline over the course of the last ~ 1000 years. Superimposed on this trend are multi-decadal to century scale fluctuations that appear to be related to changes in total solar irradiance (cf. Fig. 3), and short-term changes (generally sub-decadal length) resulting from sulfate gases and aerosols, ejected to high elevations during explosive volcanic eruptions, reducing incoming solar radiation (Mann et al., 1998). All of these "external" forcings are superimposed on, or modulate "internal" variations of the climate system such as (*inter alia*) the North Atlantic thermohaline circulation, and oscillations within the Pacific region (Mann and Park, 1994; Mann et al., 1995; Trenberth and Hurrell, 1994; Gurshunov and

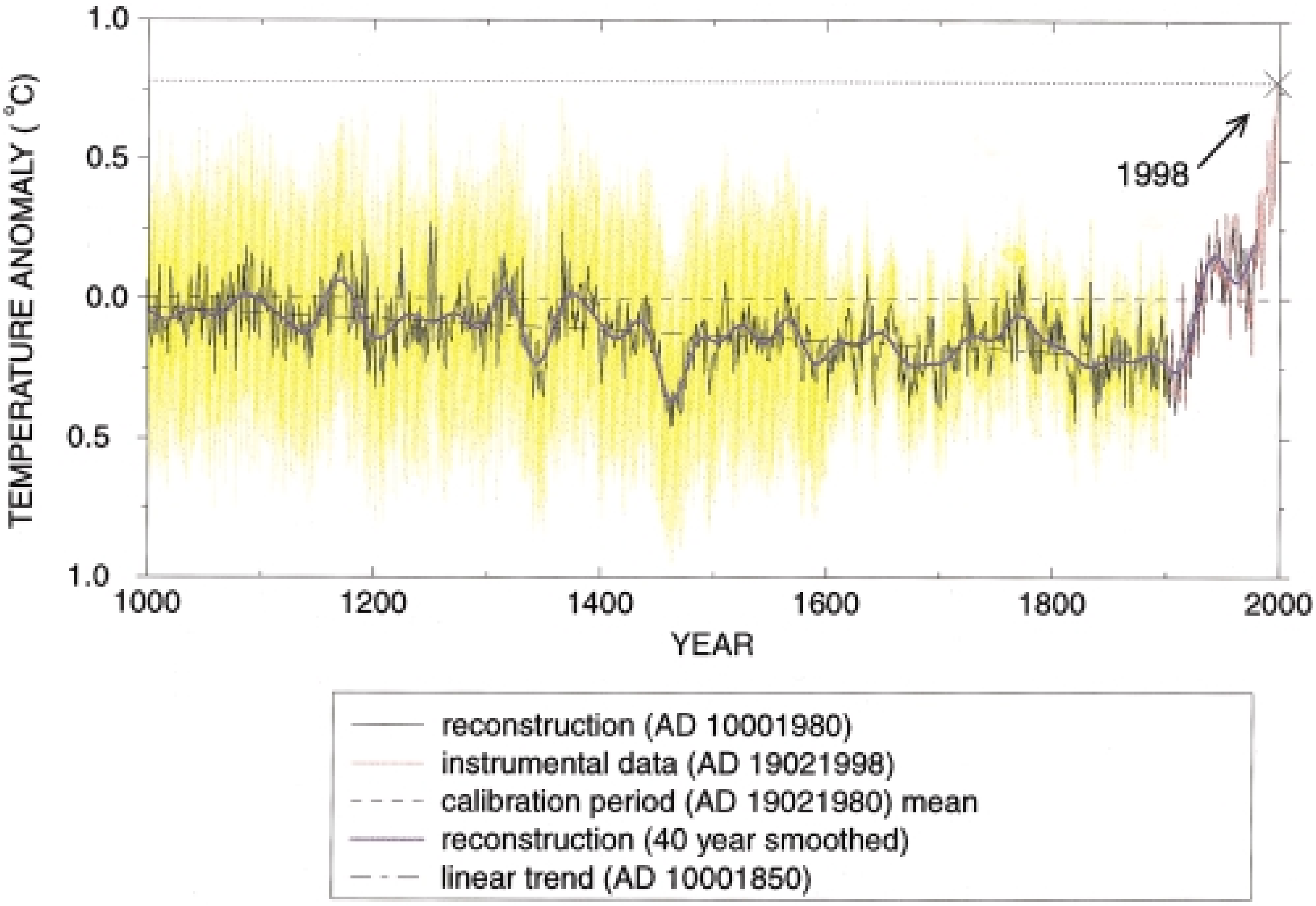


Fig. 1. Northern hemisphere mean annual temperatures (as departures from 1902–1980 means) reconstructed from a limited set of paleoclimatic records, calibrated against instrumental data for 1902–1980. The shaded area shows the confidence limits of the temperature estimates, with the uncertainty increasing back in time. The dashed line 1000–1900 shows the linear trend. Data from 1902 to 1998 are from instrumental records (from Mann et al., 1999a).

Barnett, 1998). However, in the last ~ 100 years, natural forcing factors have been overwhelmed by anthropogenic greenhouse gas increases, driving temperatures to unprecedented levels.

Fig. 1 also shows that the overall range in temperature over the last 1000 years has been quite small. For example, the range in 50-year means has only been ~ 0.5°C (from the coldest period in the 15th century, to the warmest period of the last 50 years: Table 1). Within that narrow envelope of variability, all of the significant environmental changes associated with the onset and demise of the "Little Ice Age" (~ 1450–1850) took place. This puts into vivid context the magnitude of projected future changes resulting from greenhouse-gas increases and associated feedbacks. Even the low end of model estimates suggests additional temperature increases on the order of 1–2°C by the end of the 21st century (Intergovernmental Panel on Climate Change, 1996).

The paleotemperature reconstruction of Mann et al. (1998, 1999b) also shows that abrupt, short-term changes in temperature have occurred over extensive regions. Fig. 4 shows the regional mean temperatures for North America and Europe since A.D. 1760. This period has sufficient proxy data to enable nine eigenvectors of temperature to be reconstructed, providing reliable information on the spatial patterns of climate variability at these regional scales (Mann et al., 1999b). Of particular note is the sequence of years 1834–1838. Year 1834 was the warmest in Europe over this period, with overall temperatures ~ 0.7°C above the 1902–1980 mean. However, in the next four years, temperatures systematically fell to the coldest year of the entire record - 1838 (~ 0.82°C below the 1902–1980 mean) (Fig. 4). For marginal agricultural societies, this sequence of cold years was catastrophic. In the central mountains of Norway (Synstbø), for example, harvests were damaged by early frosts, leading to starvation (Nordli, 1998) and in Japan there was widespread famine in 1836 (Mikami, personal communication). Similarly, dramatic cooling also affected North America (where 1837 was the coldest year of

Table 1
Estimated northern hemisphere mean annual temperature anomalies (°C relative to 1902–1980 mean) (data from Mann et al., 1999a)

1000 – 1099	− 0.044
1100 – 1199	− 0.043
1200 – 1299	− 0.087
1300 – 1399	− 0.064
1400 – 1499	− 0.190
1500 – 1599	− 0.135
1600 – 1699	− 0.183
1700 – 1799	− 0.137
1800 – 1899	− 0.211
1900 – 1998	+ 0.066
1900 – 1949	− 0.069
1950 – 1998	+ 0.204

Extremes of Northern Hemisphere Mean Annual Temperature, A.D. 1400–1998 (°C relative to 1902–1980 mean)

Coldest Year	1462	− 0.44	Warmest year	1998	+ 0.78
Coldest Decade	1696–1705	− 0.35	Warmest decade	1989–1998	+ 0.48
Coldest 30 years	1835–1864	− 0.24	Warmest 30 years	1969–1998	+ 0.26

Extremes of Northern Hemisphere Mean Annual Temperature, A.D. 1000–1998 (°C relative to 1902–1980 mean)

Coldest year	1462	− 0.46	Warmest year	1998	+ 0.78
Coldest decade	1458–1467	− 0.38	Warmest decade	1989–1998	+ 0.48
Coldest 30 years	1449–1478	− 0.32	Warmest 30 years	1969–1998	+ 0.26
Coldest 50 years	1453–1502	− 0.26	Warmest 50 years	1949–1998	+ 0.20

the last ~250 years). This rapid change was due to radiation and circulation anomalies associated with the explosive eruption of Coseguina in January 1835 (Bradley and Jones, 1992). Such unpredictable events clearly have a major impact on temperatures over extensive parts of the globe, yet even the largest historical eruption was small compared to numerous late Holocene eruptions recorded in Greenland ice cores (Zielinski et al., 1994; Zielinski, 1995). If similar magnitude eruptions were to occur today, the rapidity of temperature change would likely have a devastating effect on society, even in a warmer "greenhouse world".

In recent years, global climatic anomalies due to circulation changes associated with extreme phases of the El Niño/Southern Oscillation (ENSO) have had disruptive and costly effects on countries around the world. Understanding the temporal evolution and frequency characteristics of ENSO is critical to being able to develop a reliable predictive capability that may help in reducing climate-related costs. Unfortunately, the instrumental record of ENSO is limited to ~130 years (Allan et al., 1991; Können et al., 1998). Using a network of proxy climate data that collectively capture the variance of this oscillation, a longer-term reconstruction of ENSO has been produced (Mann et al., 1999c). This relies on the fact that ENSO events involve teleconnections over wide areas, leading to climatic anomalies that (*in toto*) provide information allowing a meaningful reconstruction of ENSO to be made before the period of instrumental records (cf. Stahle et al., 1998). An evolutionary spectrum of this record (Fig. 5) shows that the frequency characteristics of ENSO have not remained constant over time, and that prior to the 20th century, there was little power at the higher frequencies (i.e shorter periods: 3–7 years) typically observed in the 20th century. Indeed, in the 19th century, ENSO variability was mainly at decadal periods, but in the preceding century, ENSO variability was more like that in the 20th century. This result is similar to that based on SST reconstructions, from isotopic studies of sub-fossil coral in the Galapagos Islands, by Dunbar et al. (1994). To what extent these variations are linked to the very cold (northern hemispheric) conditions in the early to mid-19th century is not clear. However, these studies clearly demonstrate that to get a more complete understanding of the full range of ENSO variability, long-term paleorecords are absolutely essential (Cole, 1996; Dunbar and Cole, 1999). The perspective provided by instrumental data is simply too myopic.

3. A longer perspective

It is not yet possible to reconstruct global or hemispheric mean temperature over recent millennia from an extensive network of data, and any conclusions must be (cautiously) based on a more limited set of individual proxies. Where evidence from widely scattered, and diverse, proxies is supportive, confidence in such conclusions is enhanced. Here I consider a few examples. The melt record from polar ice caps is a fairly simple and

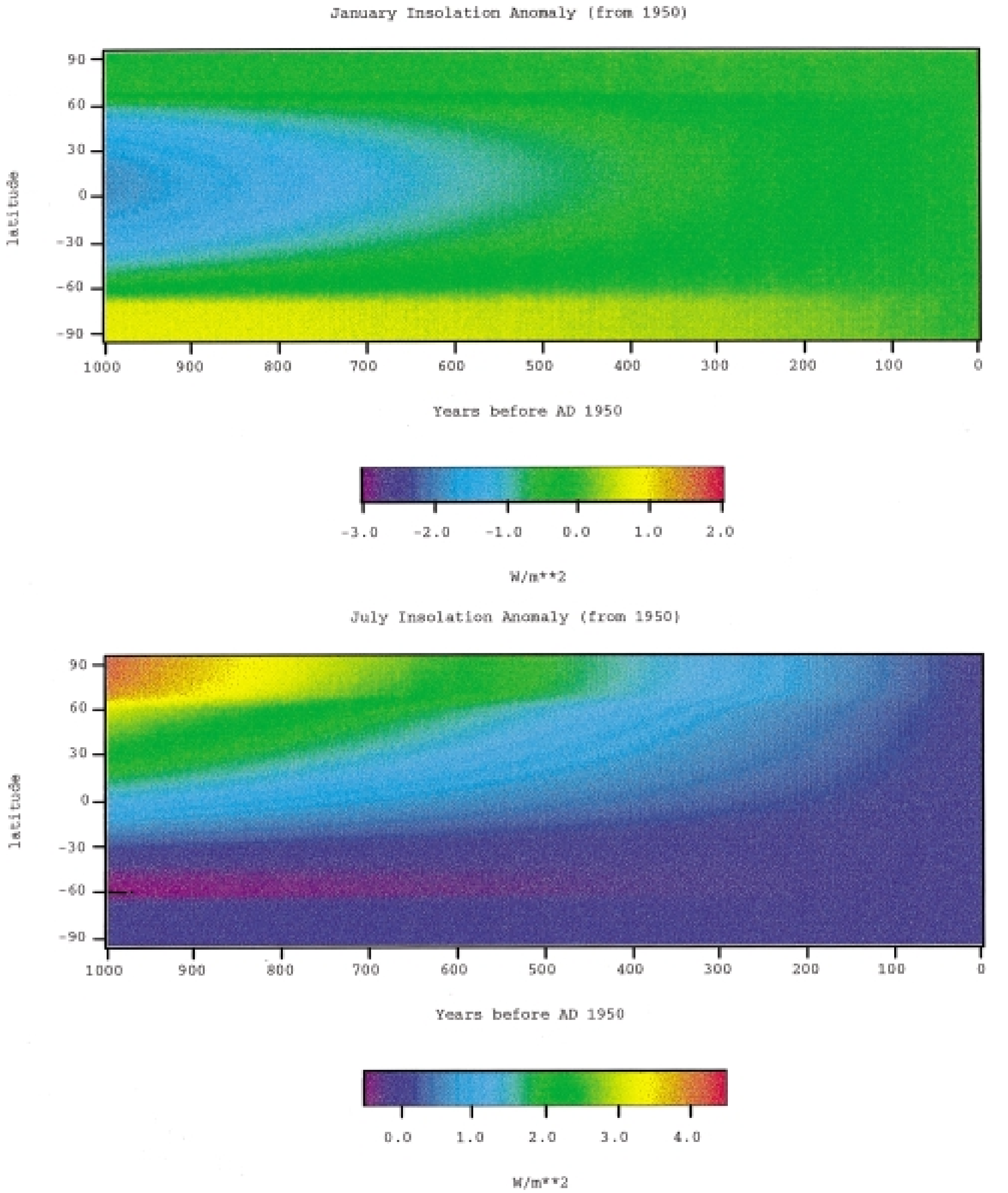


Fig. 2. January and July insolation anomalies at the top of the atmosphere (relative to 1950 values). At northern high latitudes insolation has been decreasing in July over the last millenium. (data from M.F. Loutre, pers. comm.).

Fig. 3. ^{10}Be over the last millennium, as recorded in the Greenland Ice sheet (Beer et al., 1994). Lower values of ^{10}Be represent an increase in total solar irradiance (i.e. stronger solar wind and lower production rate of cosmogenic isotopes). The data indicate higher levels of solar irradiance ~ 1000 years ago, and century-scale fluctuations over the last millennium.

direct measure of local summer temperature. Melt layers occur when surface water percolates down and re-freezes within the firn. Results from the Agassiz Ice Cap (in the Canadian High Arctic, 80.7° N, 74°W) show clear evidence of early Holocene warmth with extensive melting on this ~ 2 km high polar ice cap, driven by increased summer solar radiation as a result of orbital changes (Koerner and Fisher, 1990; Bradley, 1990). These conclusions are supported by a similar melt layer study of the GISP2 ice core (Summit, Greenland) (Alley and Anandakrishnan, 1995). Melting was virtually zero just prior to the 20th century, representing a cold episode rarely surpassed in the entire late Holocene, but in the last 75 years, it has increased to levels only exceeded twice in the last ~ 4000 years (Fig. 6: upper panel). This warming has been accompanied by increased discharge from proglacial rivers and the collpse and drainage of at least one ice marginal lake (Smith, 1997). Elsewhere on northern Ellesmere Island, mean varve thickness in Lake C2 (also an index of summer temperature) shows that temperatures in the 20th century were unusually warm, with 1931–1960 warmer than ~ 80% of the last ~ 3000 years (Lamoureux and Bradley, 1996). Conditions in the High Arctic in the 20th century were thus atypically warm compared to the rest of the late Holocene, but equally remarkable is the fact that the preceding cold episode was one of the coldest in the entire Holocene.

Varved sediments from southern Baffin Island (~ 65°N) and tree-ring studies from across the North American treeline enable quantitative paleotemperature estimates to be made, and confirm that summer temperatures were considerably lower in the 18th and 19th centuries compared to the warmest decades of the 20th century. On southeastern Baffin Island, for example, mean June temperatures were ~ 2°C lower from A.D. 1700–1900 than in the last 50 years, leading to less snow and ice melting, reduced runoff and minimal sediment flux to rivers and lakes (Hughen et al., 1999). During this period, upland plateaux were extensively and persistently snow-covered, tundra vegetation on the hilltops was killed, and glaciers advanced to positions commonly more extensive than at any time in the Holocene (Locke and Locke, 1977). Studies of rings in trees at the boreal forest limit in North America suggest that mean annual temperatures in this region were ~ 2°C lower in the early to mid-19th century compared to conditions only 100 years later (D'Arrigo & Jacoby, 1992,1993). These and other records (cf. Overpeck et al., 1997) suggest that in the last 150–200 years, temperatures at high latitudes have increased rapidly, with many areas experiencing both the warmest and the coldest (multi-decadal) episodes of (at least) the last few thousand years. Thus, the rate of temperature change to which these marginal environments have been subjected has been unprecedented for at least several millennia.

Macrofossils (sub-fossil trees and branches) located above present treeline in the Scandes Mountains of Sweden provide another record indicative of summer temperature throughout the Holocene. The upper limit of trees in this region is very sensitive to summer temperature (Briffa et al., 1990). By mapping the uppermost occurrence of trees (as recorded by remnant pieces of *in situ* sub-fossil wood) a record of summer paleotemperature is revealed. Because a very large number of samples has been collected and dated, a fairly complete record of Holocene treeline changes can be reconstructed (Fig. 6:

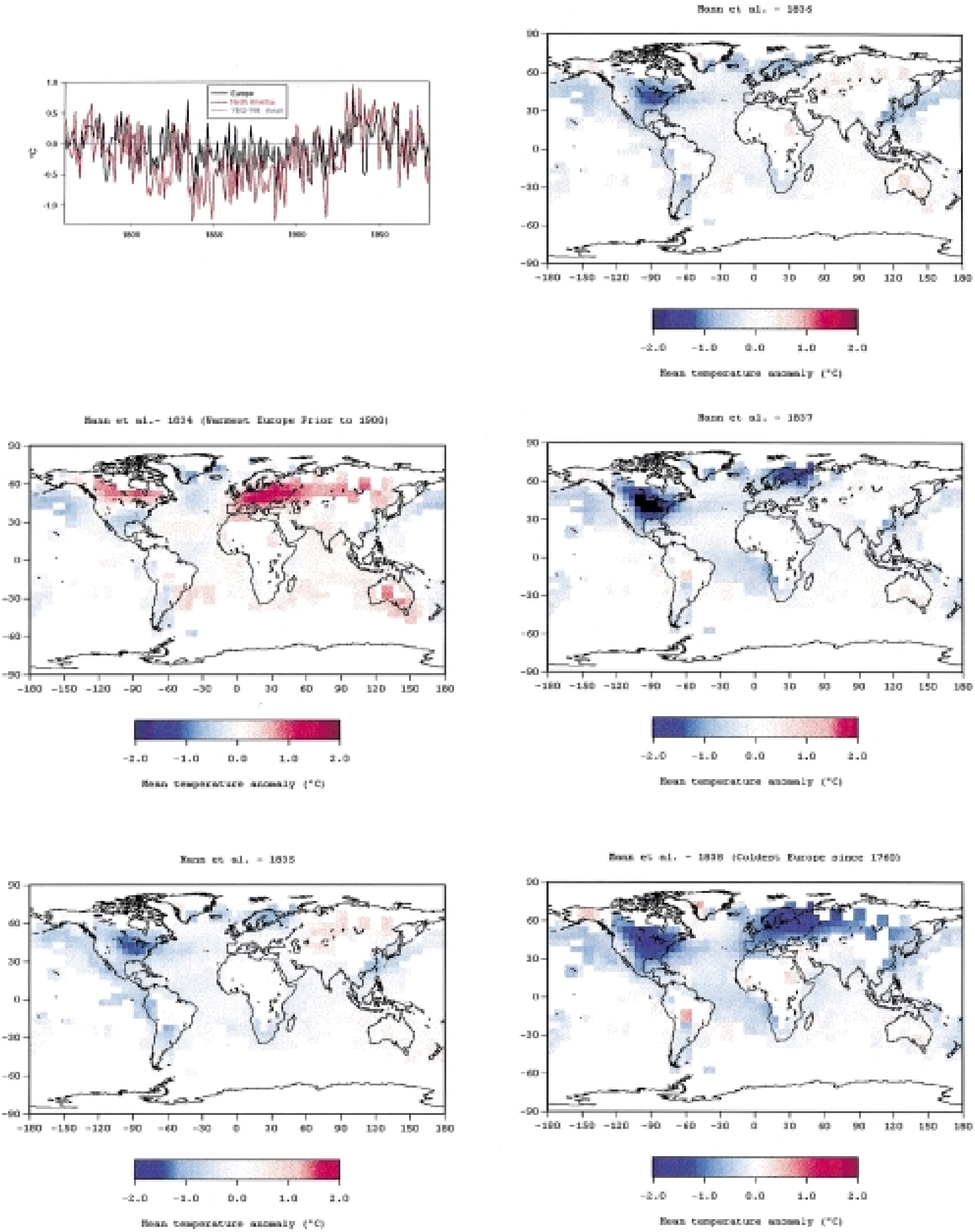


Fig. 4. Mean annual temperature anomalies for Europe (37.5° 57.5°N, 7.5°W – 32.5°E) and North America (30–60°N, 70–125°W) since A.D. 1760, relative to the 1902–80 mean [top left panel]. Other panels show mean temperature patterns for 1834 (the warmest year in Europe prior to the late 20th century) and for 1835–1838. Temperatures rapidly fell following the eruption of Coseguina (Nicaragua) in January 1835. 1837 was the coldest year of the record for North America and 1838 was the coldest for Europe (data from Mann et al., 1998; 1999b).

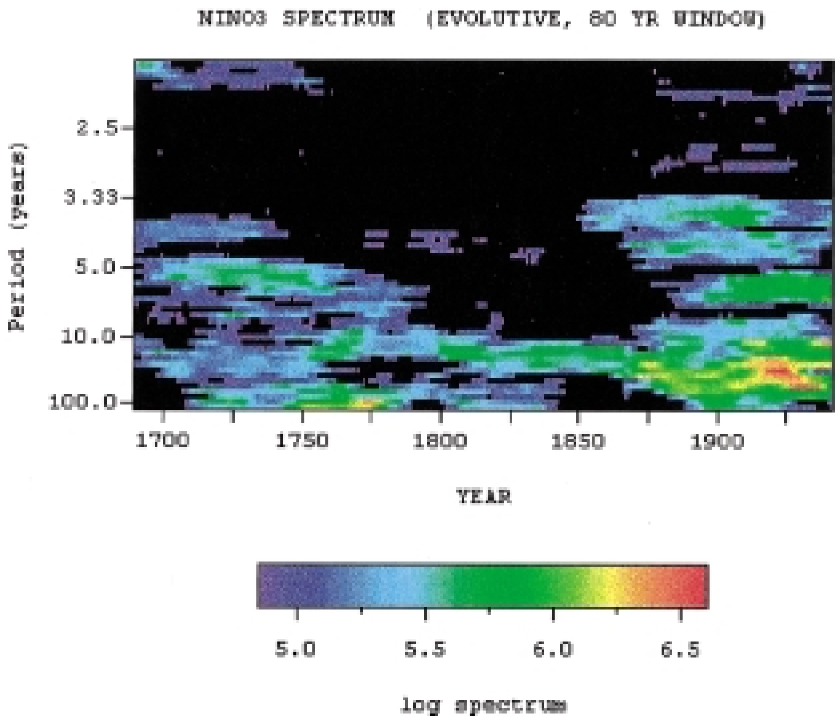
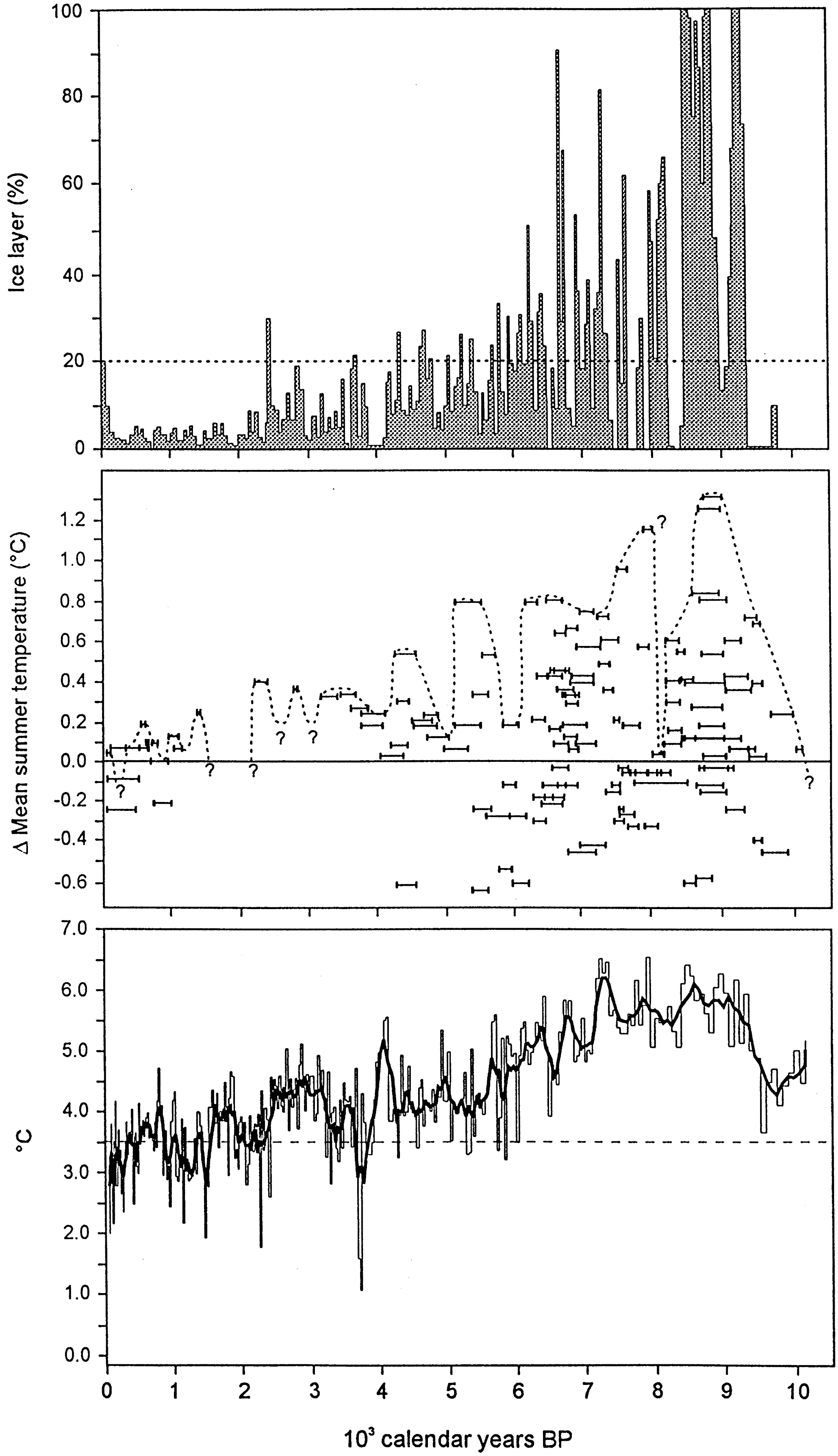


Fig. 5. Evolutive spectrum of sea surface temperatures over the Niño3 area of the equatorial Pacific (5°N–5°S, 90–150°W) using an 80 year moving window. Niño3 is commonly used as a diagnostic indicator of El Niño-Southern Oscillation conditions. Concentrations of power are shown in the brighter colors. The frequency distribution of SSTs in the first half of the 20th century was not typical of the cold 19th century, but was similar to that in the slightly warmer 18th century. If our understanding of ENSO was based solely on the period of instrumental records (since ~1860) the long-term changes in the spectrum of SSTs would not be apparent.

middle panel). Like the Agassiz Ice Cap summer melt record, cooling throughout the Holocene is again clearly revealed, with the most recent cold episode also being one of the most severe in the entire record. Further insight into the biological significance of this period is provided by studies at the treeline in the northern Ural Mountans of Russia (Shiyatov, 1993). There, *in situ* subfossil trees were cross-dated to provide precise information on when each tree was established and when it died (Fig. 7). This study shows that in the 12th and 13th centuries, trees were able to establish themselves and grow successfully at elevations up to 340 m a.s.l., but over the next ~400 years, the upper limit for tree establishment gradually declined, many high elevation trees died, and from ~1750 to 1950 no seedlings at all were able to survive above 280 m. This situation has only changed in the last ~50 years and trees are once again becoming established at elevations above 300 m in this region.

Finally, one other unique high latitude proxy also provides evidence for an overall Holocene cooling trend, punctuated by decade-to-century scale anomalies. A stalagmite $\delta^{18}O$ record from northern Norway (considered to be a proxy of local mean annual air temperature)

Fig. 6. Selected Holocene paleotemperature records from high latitude sites in the northern hemisphere. *Upper panel*: The record of summer melting on the Agassiz Ice Cap, northern Ellesmere Island, Canada over the course of the Holocene. Percent melt indicates the fraction of each core section containing evidence of melting. Melting in the 20th century is greater than almost all periods for ~4000 years (see dashed line). During the cold episode preceding the 20th century no melting occurred. This was one of the coldest periods in the entire Holocene (from Koerner and Fisher, 1990). *Middle panel*: Summer temperature anomalies estimated from the elevation of ^{14}C dated sub-fossil pine wood samples (Pinus sylvestris L.) in the Scandes mountains, central Sweden (black bars) relative to temperatures at the modern pine limit in the region (after adjustment for isostatic rebound during the Holocene). Wood samples were ^{14}C dated close to the core of each sample to obtain an age near the time of germination. Upper limit of pine growth is indicated by the dashed line. Changes in temperature were estimated by assuming a lapse rate of 0.6°C 100 m^{-1}. The overall decline in Holocene temperature is evident as is the exceptionally cold period preceding the 20th century. (from Dahl and Nesje 1996, based on samples collected by L. Kullman and G. and J. Lundqvist). *Lower panel*: Paleotemperature reconstruction from oxygen isotopes in calcite sampled along the growth axis of a stalagmite from a cave at Mo i Rana, in northern Norway. Samples were taken every 1 mm, corresponding to a resolution of ~25–30 years. Linear interpolation between 12 TIMS U-series dates along the stalagmite provide a timescale in calendar years, with an average error of 10-50 years. Growth ceased around A.D. 1750. (from Lauritzen, 1996; Lauritzen and Lundberg, 1998).



Ice layer (%)
100
80
60
40
20
0
Δ Mean summer temperature (°C)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
?
°C
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0
1
2
3
4
5
6
7
8
9
10
10^3 calendar years BP

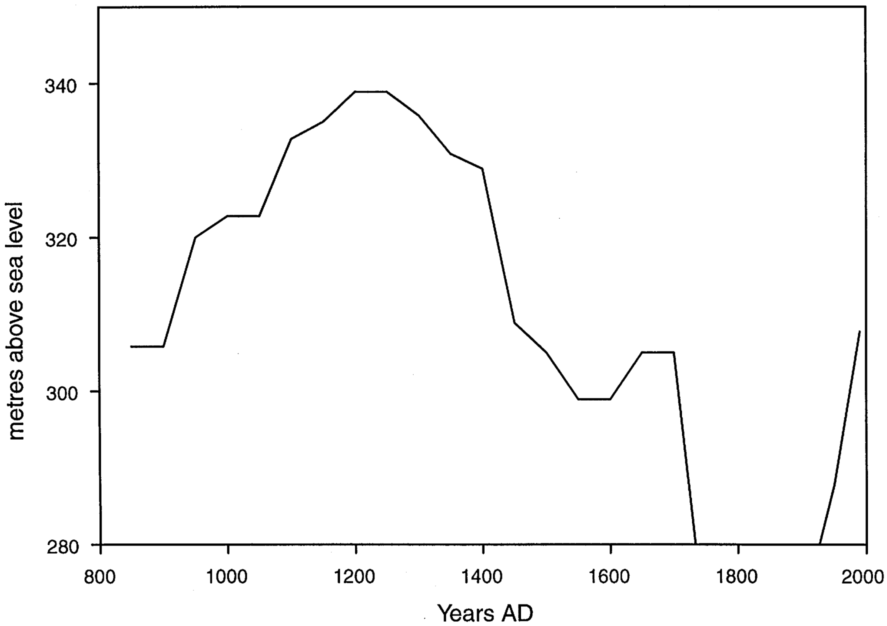


Fig. 7. The uppermost limit of trees growing above modern treeline in the northern Ural mountains of Russia, based on dendrochronologically dated sub-fossil tree stumps. Trees were able to colonize slopes up to 80 m above present treeline around A.D. 1100–1200, whereas from 1750–1950, no trees were able to successfully survive above modern treeline. (from Shiyatov, 1993).

shows an overall decline, culminating in the exceptionally cold episode of recent centuries (Lauritzen, 1996; Lauritzen and Lundberg, 1998; Fig. 6: lower panel). This record also indicates there were rather abrupt shifts in ^{18}O at times, with extreme short-lived anomalies (e.g. at ~ 3700 calendar years B.P.). This site is sensitive to conditions in the northern North Atlantic and the abrupt changes are indicative of sea surface temperature and /or circulation anomalies over this region.

High-resolution paleoclimate records from low latitudes also document the unusual nature of the last few centuries. In recent decades, glaciers and ice caps have disappeared altogether in many high mountain locations in the Tropics (Schubert, 1992; Hastenrath and Kruss, 1992). Ice core data enable these observations to be placed in a longer temporal perspective. The ice core from Huascarán, Peru, for example, shows that $\delta^{18}O$ (considered to be a proxy for temperature) rose from the lowest values in the Holocene during the 17th and 18th centuries, to recent values that are higher than at any time in the last 6000 years (Thompson et al., 1995a). At Quelccaya Ice Cap (southeastern Peru), the lowest $\delta^{18}O$ values of the 1500 year record at that site were recorded from ~ 1530 to 1900 and within the last 20 years, melting has reached the summit (5670 m) which is unprecedented in the entire paleorecord (Thompson et al., 1986 Thompson, 1996,1999). Ice cores from the Gregoriev Ice Cap (in the Pamirs), and Guliya and Dunde Ice Caps (Tibet) also show evidence of recent warming (Thompson et al., 1995b; Lin et al., 1995; Yao et al., 1995). At Dunde, $\delta^{18}O$ values were higher in the last 50 years than in any other 50 year period over the last 12,000 years. These records all point to a dramatic climatic change in recent decades (cf. Liu and Chen, 1999) prompting concern over the possible loss of these unique archives of paleo-environmental history (Thompson et al., 1993).

All of these quite different paleorecords from high and low latitude sites lead to the same conclusion — summer temperatures which gradually declined over the Holocene, culminated in an exceptionally cold period during the last few centuries (the "Little Ice Age" *sensu lato*, ~ 1450–1850). This unusual period was terminated by rapid warming in the 20th century, with temperatures reaching unprecedented levels compared to the last several thousand years. The overall Holocene temperature decline was apparently a response to orbital forcing (declining boreal summer insolation). Superimposed on that trend were century-to-decadal scale anomalies, which may have been driven by changes in total irradiance, periods of prolonged volcanic explosivity and/or internal oscillations within the climate system (Mann et al., 1998, 1999b,c). However, the magnitude and rate of temperature change in the 20th century is unprecedented and strongly correlated with changes in greenhouse gases. It seems highly unlikely that natural variability alone can explain the changes in temperature recorded so diligently by instrumental observers over the past ~ 150 years. Paleoclimatic records have been essential in reaching this conclusion.

4. Conclusions

With the ever-increasing impact of society on the global climate system, there is an urgent need to understand how climate may change in the future. This requires knowledge of both natural and anthropogenic forcing, and of the climate response to both. Paleoclimatic records are essential tools in this endeavour. They clearly demonstrate that the last century has been warmer in many areas than for several millennia, and that this warming followed one of the coldest periods of the late Holocene. Thus the rate of temperature change to which ecosystems and society have been subjected over the last ~ 150 years has had no analog for thousands of years.

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