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Section E: SUMMARY

33 Climatic variations over the last 500 years

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33.1 Introduction

The period since A.D. 1500 has seen dramatic changes in the fortunes of human life on this planet. At the turn of the 16th century the New World and tropical and southern Africa had just been discovered by European colonists, and only the Australian and Antarctic continents remained unknown to the outside world. At the beginning of the 16th century scientific understanding was extremely limited; the earth was believed to be only about 6000 years old and the Polish astronomer, Mikolaj Kopernik (Copernicus) was developing his theory that the earth and the other planets move around the sun. Almost 500 years on, at the dawn of a new millennium, satellites have reached every planet in our solar system except Pluto and the world's population is linked by instant communications. From a population of only about 400 million in A.D. 1500, the world now supports over 5 billion people.

Over this time, scientific understanding of the environment of our planet has increased to such an extent that we can now model the physics that underlies most of the processes of nature. In the field of climatology this increase in understanding has been dramatic over the last 25 years but there is still much that remains unknown. This is particularly true about the record of past climatic variations and their causes. The first attempts to estimate average hemispheric and global mean temperatures were made about a century ago (Köppen, 1873) and possible explanations were postulated for the changes in temperature which were seen since 1750. Despite these temperature series showing large interdecadal variability, most meteorologists during the first half of the 20th century believed that climate did not change by significant amounts. Climatology was generally considered to be the least fashionable aspect of meteorology (Lamb, 1977).

At present, the possibility that climate is changing and that this may lead to unprecedented warming, is at the top of the political agenda (Bromley, 1990). The increase in global mean temperatures by 0.3-0.6°C, since the middle of the 19th century (Folland *et al.*, 1990) is often cited as evidence that anthropogenic increases in greenhouse gases are affecting the climate. While the extent to which human activities have contributed to global warming over the last century is debateable, this uncertainty has highlighted the greater understanding of climate and climatic change that is required.

Greater understanding of climatic fluctuations is necessary, not only of the last century, but also of earlier times. The longer the record of global climate is, the more confidence we will have in determining how unusual recent events have been. In this volume we have provided a comprehensive assessment of climatic change covering the period since A.D. 1500. We are, therefore, in an excellent opposition to review both what has happened since that time and also to consider what some of the causes of the changes might have been. We begin, however, with a reconsideration of some of the proxy climatic reconstruction techniques and their limitations. These comments provide a caveat to those who would over-interpret the reconstructions, and serve to focus attention on where further methodological research is needed.

33.2 Reconstruction techniques

33.2.1 *Seasonal limitations*

In any proxy climatic reconstruction it is likely that the parameter being used (e.g. tree ring growth, ice core isotopic value) reflects climate during a particular season of the year. For example, historical records of variables such as grape flowering and harvest dates or snow cover duration are seasonally specific. Stating that the 17th century was cooler than the 20th based on greater numbers of days of snow lying may not be correct if the non-winter seasons were warmer. Similarly, ice core parameters such as $\delta^{18}O$ only represent conditions during periods of snowfall. Extremely cool periods during intense inversions, when there is no snowfall, will not be represented in annual time series. By contrast, ice core melt records reflect summer temperatures. Tree growth indices are largely indicative of conditions during the growing season, but they may also reflect preceeding conditions which influence soil moisture (or the physiological condition of the tree) prior to the growing season. Determining the correct seasonal signal in a particular proxy record is often one of the most difficult problems in paleoclimatic reconstruction. Much of the evidence presented in this book (particularly the concluding discussion which follows below) relates to conditions during the growing season, or the snowfall season over ice caps and glaciers. The temptation to extrapolate conditions in one season to the year as a whole must be resisted. Where multi-season reconstructions are available, as in Switzerland or the western Soviet Union, important differences are often apparent (cf. Figure 6.4 in Pfister, Chapter 6 and Figure 9.2 in Borisenkov, Chapter 9).

33.2.2 *Temporal and spatial limitations*

Limitations in the temporal resolution of some climate reconstructions are not always recognised. For example, in dendroclimatic reconstructions long chronologies have often been derived from a combination of living and standing dead trees, stumps and sub fossil material. If all the overlapping samples cover a relatively short period of time, it would be impossible to consider variations on longer time scales than the average length of the samples. Perhaps more significantly for studies the last 500 years, all tree-ring time series require some form of standardization to remove biologically-related age trends. The degree to which low-frequency aspects of chronologies are altered by this process is a matter for much debate (see Chapters 15, 19 and 24 by D'Arrigo and Jacoby, Briffa and Schweingruber, and Norton and Palmer). It is also true that the magnitude of yearly and decadal anomalies in any final chronology will be determined by the type of curve fitting procedure adopted (Cook and Kariukstis, 1990).

Historical records may also contain a temporal bias. Observers base descriptive comments about climate on their prior experience. Many early North American pioneers considered their first few winters harsh after their experience of much milder winters in Western Europe. With time, their opinions of the unusual or severe may change leading to a bias in what might otherwise appear to be a long and continuous record. Because of all these uncertainties, it should be apparent that no one record can be entirely relied upon to represent a faithful reconstruction unless there is corroborating evidence from another, independent source. The more supporting lines of evidence, the stronger will be the basis for confidence in the reconstructions. Each supporting line of evidence provides a further building block to which subsequent work can be added. In this way, a complex inferential pyramid of information is gradually constructed leading to a true and meaningful picture of climatic conditions in the past.

With ice cores, the climatic interpretation of certain parameters is problematical, particularly for the relatively small amplitude changes observed over the last 500 years. In polar regions, values of $\delta^{18}O$ and δD in snowfall decrease with decreasing condensation temperature in clouds, but the quantitative nature of these relationships are generally derived from the spatial (geographic) dependence between isotopic ratios in snowfall and mean annual temperature. Unfortunately temporal relationships may not be the same as the spatial relationship (see Section 28.3.2 in Peel, Chapter 28) and this may lead to incorrect paleoclimatic interpretations. Furthermore, different moisture sources can lead to apparent differences in reconstructed temperature, even when none occurred. Peel (Chapter 28) shows that it is essential to consider changes in moisture source when trying to understand the isotopic record from the Antarctic Peninsula region, and similar considerations are required in other regions of the world (Johnsen *et al.*, 1989).

Much effort in recent years has gone into reconstructing large scale (hemispheric or globally averaged) changes of temperature and precipitation from instrumental records (e.g. Jones *et al.*,1986a, 1986b, 1991; Bottomley *et al.*, 1990; Hansen and Lebedeff, 1988; Bradley *et al.*, 1987a; Diaz *et al.*, 1989; Vinnikov *et al.* 1990). Most of these records only extend back into the mid or late 19th century. What can we say about large-scale climatic changes further back in time? This is an extremely difficult problem since data from the oceans (70% of the globe) peters out in the mid-19th century and vast areas of the tropics (and much of the Southern Hemisphere) are similarly devoid of observations. At the present time it is simply not possible to derive a 'global' time series beyond the mid-19th century. Indeed such a record may be tenuous beyond the early part of this century (Bradley, 1991).

Can a hemispheric record be produced? There are currently far too few records to derive a meaningful long-term Southern Hemisphere record. Even today, instrumental records are only available for about 75% of the hemisphere and this coverage rapidly deteriorates back in time. In the Northern Hemisphere we are approaching the point where it may be possible to derive a long time series, combining tree ring, historical and ice core data. However, the problems of seasonal representation, discussed above, suggest that such an effort would have to focus on only one season, probably the summer. This may not be representative of the year as a whole. For example, in the Northern Hemisphere instrumental record there have been negligible changes in temperature since the mid-ninteenth century. Most of the long-term warming has occurred in the other three seasons (Jones and Bradley, Chapter 13).

Problems still prevail concerning large areas of the Tropics and much of interior Asia for which we have virtually no high resolution information. Nevertheless, with the development of new chronologies and techniques of climatic reconstruction we anticipate that a fairly good northern hemispheric summer temperature reconstruction, spanning several centuries, may be assembled within a few years. Previous attempts at such a synthesis (Groveman and Landsberg, 1981) are based on too few records (many of which were not properly calibrated in terms of climatic response) to provide a reliable time series.

An alternative approach would be to select those regions of the world which are known to be highly correlated with the hemispheric record of the last century (Bradley, 1991). If this can be demonstrated, regional records might be considered as proxies of larger scale variations. This requires the assumption that the relationship observed in the last century has prevailed over longer periods but there is evidence that this may not have been the case (Jones and Kelly, 1983). Nevertheless, such an assumption is no different from that made in all paleoclimatic reconstructions, that the relationships observed during the period of instrumental records (the calibration period) remained constant during earlier periods. The use of a regional time series to represent the hemisphere uses the same assumption, substituting a spatial frame of reference for a temporal one. Further consideration of such an approach is recommended.

33.3 Regional evidence

33.3.1 Europe

The European region is the part of the world with the most detailed climate history. Instrumental records discussed by Jones and Bradley (Chapter 13) extend back to the late 17th and early 18th century. Because meteorological instruments were developed in Europe, detailed information is available for Europe for about 100 more years than for any other continent. Prior to the instrumental time there is a wealth of written historical information back several hundred years further. This depth of climatic information from both instrumental and historical sources has meant that many of the 'generally' understood climatic variations of the last 1000 years were first recognized in Europe. Many methods of climatic reconstruction have been tested in Europe where the long records enable detailed verification of the results to be undertaken.

From the evidence presented for Europe in Chapters 5-9 and 18-20, the climate since A.D. 1500 has varied between extremely warm and extremely cool decades, but few of these decades appear synchronous over the whole of the European continent, from the Iberian Peninsula to the Urals. Evidence for a period of protracted cool temperatures during the so-called Little Ice Age during the 16th to 19th centuries does not appear that convincing. The best documented and most widespread cool periods occurred during the 17th and 19th centuries.

From warm temperatures during some decades of the early 16th century, conditions gradually began to cool during the second half of the century. Over Western Europe tree ring evidence indicates cool temperatures during the 1560s and 1570s (Serre-Bachet *et al*, Chapter 18). The severity of winters in northern Italy increased in frequency during the period 1570 to

1614, with milder conditions later in the first half of the 17th century (Camuffo and Enzi, Chapter 7). The decades of the 1590s and the 1600s were cool over northern Europe (Briffa and Schweingruber, Chapter 19) and in the northern Urals (Graybill and Shiyatov, Chapter 20). However, cool winters and springs were more common in Iceland during the 1630s and 1690s (Ogilvie, Chapter 5). In western parts of the USSR, winter and spring seasons were cooler in the 17th century than the first half of the 16th century though summers and autumns showed little difference (Borisenkov, Chapter 9).

Cool conditions returned to the European region during the late 18th and early 19th centuries. The frequency of severe winters in northern Italy increased again in the late 18th century (Camuffo and Enzi, Chapter 7). The number of cooler winters and springs and greater sea-ice extent off Iceland also increased at the same time (Ogilvie, Chapter 5). The 1800s and 1810s were cold throughout most of western Europe, as shown by evidence from Switzerland (Pfister, Chapter 6) southwestern Europe (Serre-Bachet *et al.*, Chapter 18) and northern Europe (Briffa and Schweingruber, Chapter 19). According to the Swiss reconstructions, all seasons were cold during this period. However, further east, in the western Soviet Union, temperatures were warmer than the average during the summer and autumn seasons. Indeed, this was the period of the warmest summers in the entire 500 year period (Borisenkov, Chapter 9). In the northern Urals, however, relatively cool conditions seem to have prevailed (Graybill and Shiyatov, Chapter 20). A lack of sea-ice off Iceland is apparent during the first half of the 18th century (Ogilvie, Chapter 5) though summer temperatures in Svalbard appear to have been low at this time (Tarussov, Chapter 26).

Following the 1810s many European records indicate warmth during the 1820s followed by a return to cool conditions during the 1830s. This cold-warm-cold oscillation is evident in many of the proxy records discussed here as well as in most European instrumental records that extend to the period (Jones and Bradley, Chapter 13). Conditions were cooler again during the second half of the nineteenth century, particularly over the western USSR where the coldest summers of the last 500 years were experienced (Borisenkov, Chapter 9; Graybill and Shiyatov, Chapter 20; Jones and Bradley, Chapter 13).

In between these two relatively cooler centuries, the 18th century shows evidence of warmer conditions. For example, the instrumental record for Central England (Manley, 1974) indicates that temperatures were generally warmer than during the 19th century particularly during the 1730s. Warmth at this time is also indicated in Switzerland (Pfister, Chapter 6) and during the 1750s and 1760s in northern Europe (Briffa and Schweingruber, Chapter 19) and in the northern Urals (Graybill and Shiyatov, Chapter 20). Summers were 1°C warmer than the long-term average in the western U.S.S.R during the late 18th century.

33.3.2 Asia

Long-term climatic reconstructions for Asia have largely been confined to the eastern Asian region encompassing China and Japan. Reconstructions elsewhere on the continent are extremely scarce. Although the area is renowned for long historical records, there are actually very few for western China and the Asian interior and, as yet, very little is known about historical climatic records from south and southeast Asia. Dendroclimatic studies may hold the key to a better unnderstanding of past climatic variations in the Asian interior.

Some of the first dendroclimatic reconstructions from the Himalayas and Tibet are presented in this volume (Hughes, Chapter 21; Wu, Chapter 22).

The relatively few reconstructions available for the continent show no evidence of any prolonged periods of anomalous temperatures. Indeed, from the reconstruction of *summer* temperatures in Beijing (Wang *et al.*, Chapter 11) extending back to 1725, the coolest period occurred during the 1960s. This contrasts strongly with the isotopic record from the Dunde ice cap further west (see below). The long temperature reconstructions from maximum latewood density in Kashmir for the spring and late summer periods (Hughes, Chapter 21) and those for summer in western China (Wu, Chapter 22) also show no trends over the last three centuries. The coldest period of the last 400 years in western China was ~1600-1670 and in northeast China it was the 1650s and 1660s. In Kashmir, dendroclimatic records only extend to 1690; the coolest decades of the last 300 years were during the 1720s and 1730s and 1790-1840. Reconstructions indicate warm decades in Kashmir during the mid-1700s and in western China during the mid-16th century, the early 18th century and again in the early 19th century.

Oxygen isotope measurements from the Dunde ice cap in western China (Thompson, Chapter 27) seem to confirm dendroclimatic evidence of cooler conditions during the late 16th and early 17th centuries (particularly from ~1580-1650) and to a lesser extent during the 19th century. The 18th century was warmer. The years since 1920 are the warmest of the entire series.

Reconstructions of precipitation totals from the clear and rain day records in China and Japan (Wang and Zhang, Chapter 10; Murata, Chapter 12) show evidence of decadal scale variations during the 18th century but no long-term trends. At the Chinese sites, summer precipitation was low during the 1740s and again during the 1770s and 1780s with wetter conditions during the 1750s and 1760s. The Japanese reconstructions show quite complex features over different regions of southern Kyushu. Drier conditions are evident during the late eighteenth century (1780s, 1790s) with a tendency towards wetter conditions during the 1740s and 1750s. The reconstructions in the two countries therefore appear to be in phase only at certain times.

33.3.3 North America

Historical evidence from the North American region is confined to the time since the European settlement. Climate reconstruction on the year-to-year time scale further back in time is only possible using tree-ring and ice core evidence. Diaries kept by the early settlers in the northeastern United States reveal warmer conditions during the 1740s and cooler annual temperatures during the 1750s, 1760s and 1810s (Baron, Chapter 4). No prolonged periods of cool temperatures are evident between 1640 and 1820. Further north in Canada the historical archives kept by the Hudsons Bay Company have been used to estimate temperatures and sea ice severity around Hudsons Bay during the 18th and 19th centuries (Ball, Chapter 3; Catchpole, Chapter 2). The sea ice records reveal the worst sea ice severity years during the 1810s and 1840s.

Over the western third of the United States, Fritts and Shao (Chapter 14) have reconstructed temperatures from tree-ring information back to 1602 for five regions. All regions show little evidence of protracted cool periods with the coldest period occurring during the late 19th and early 20th centuries. Prior to this time the 1750s to 1770s were cool, as were the 1830s and 1840s. Warm conditions occurred during the 1930s and 1950s and during the 1850s and 1860s. The period from about 1650 to 1740 was also generally warm, particularly over northern parts of the western United States. Average conditions from 1602-1900 were warmer and drier over most of the western United States compared to the period since 1900.

D'Arrigo and Jacoby (Chapter 15) reconstructed annual temperatures for northern North America from trees growing along the Canadian tree line from the Yukon to Quebec. Cooler temperatures occurred during 1725 to 1800 and again during the second half of the 19th century. The present century is clearly the warmest century in their reconstruction.

Tree-ring information from the central and eastern United States (Meko, Chapter 16; Cook *et al.*, Chapter 17) has been used to assess drought frequency since the early 18th century. Both reconstructions show little evidence of prolonged periods of drought or of *widespread* droughts, except possibly during the 1750s and 1760s and from 1814 to 1822. Fritts and Shao (Chapter 14) examined their reconstructions for the period 1814-1822 and found below normal precipitation during winter, spring and autumn months and above normal temperatures during summer.

In many regions drought appears to have occurred more regularly during the eighteenth century and again during the period after 1920. However, droughts which are significant locally may not have been widespread. Meko (Chapter 16) notes that although the 1930s and 1950s experienced severe droughts, there were longer, more persistent droughts which occurred earlier though these were less geographically extensive. The major feature of a number of regions is a lower frequency of droughts during the second half of the 19th century. Fritts and Shao (Chapter 14) postulate more frequent storms between 1600 and 1900 than since 1901.

In northern Canada, ice core melt records suggest that summer temperatures were generally low from ~1570-1860, with coldest conditions from 1550-1620 and ~1680-1700 (Fisher and Koerner, 1983; Alt, 1985). At Camp Century, Greenland, coldest conditions appear to have been in the 17th century (Dansgaard *et al.*, 1975). Holdsworth *et al.*, (Chapter 25) using an ice core from Mt. Logan in the Yukon show $\delta^{18}O$ values were below the long-term average from ~1850-1950 and above average for the period 1740-1850. However, these changes may not be linked to temperature in the same way as in polar regions.

33.3.4 Southern hemisphere

The greater area of ocean in this hemisphere considerably limits the number and extent of climatic reconstructions available. Written historical evidence is limited to the period since European settlement. Records from the time of the Spanish conquistadors have been used by Quinn and Neal (Chapter 32) to reconstruct a record of El Niño occurrence. Elsewhere in this hemisphere evidence is generally only available from tree-ring and ice core sources.

Tree-ring evidence from the hemisphere has been confined to southern South America, New Zealand and Tasmania. There is potential in parts of continental Australia and southern Africa but as yet this has not been fulfilled. Climatic reconstructions in New Zealand are, at present, limited by the age of species so far used. Dendroclimatic reconstructions have yet to be made from the longer lived species in the region. The main feature of the temperature reconstructions back to 1750 (Norton and Palmer, Chapter 24) is a cool period during the

1840s and 1860s (1860s and 1870s in Tasmania) that agrees with the earliest instrumental records available (Salinger, 1981). Since the coming of Europeans to New Zealand in 1840 there has been a widespread retreat of most mountain glaciers (Gellatly and Norton, 1984; Gellatly, 1985).

In southern South America longer chronologies have been produced from both coniferous and deciduous species. Temperature reconstructions have been made for both Patagonia and Tierra del Fuego, back to 1500 and 1750, respectively (Boninsegna, Chapter 23). All records show a great deal of decadal-scale variability but the cooler summers are apparent from 1500-1650 in central Patagonia and the latter half of the 17th and 18th centuries in northern Patagonia. In Tierra del Fuego, lowest summer temperatures occurred in the late 1800s. Hence there is no dendroclimatic evidence for a protracted "Little Ice Age" period in Patagonia.

Ice core evidence in this hemisphere is confined to the Quelccaya ice cap in Peru and to Antarctica. The Quelccaya record (Thompson, Chapter 27) indicates lighter isotopic values from about A.D. 1540 to the 1810s. The 1810s appear to have been the coldest decade of the entire record (recording the greatest heavy isotope depletion). By contrast, the 1820s were the warmest decade of the 19th century and temperatures have increased considerably since then.

In Antarctica, different ice cores reveal markedly different isotopic records, indicating that either a simple temperature interpretation is not possible, or persistent regional variations in anomalies and trends occurred in the past (Mosley-Thompson, Chapter 29). For example, the Mizuho record clearly shows a period of low $\delta^{18}O$ values from ~1630-1870, whereas at the South Pole the lowest values are in the 16th century with a generally 'cold' (low $\delta^{18}O$) period from ~1540-1740 (interrupted by a warmer period from ~1630-1670). At Law Dome the coldest interval is from ~1730 to the early 1900s, whereas towards the Antarctic Peninsula (Siple) and on the Filchner-Ronne ice shelf there is no clear picture of prolonged low $\delta^{18}O$ values.

Over the Antarctic Peninsula the interpretation of the isotope record is considerably more complex than elsewhere in Antarctica (Peel, Chapter 28). Peel shows that it is essential to derive both $\delta^{18}O$ and δD ratios in order to assist with the interpretation of the isotope/temperature record because isotopically light features may be related to polynya formation in the Weddell Sea. The resulting moisture source changes affect the isotopic ratios. In this region, where records currently only extend back to 1800, the first tentative reconstructions show that cool conditions prevailed in the 1860s, 1890s and 1930s.

33.4 Evidence for changes in possible forcing factors

Three possible forcing factors were considered in this volume: solar irradiance changes (Stuiver and Braziunas, Chapter 30) volcanic events (Bradley and Jones, Chapter 31) and changes in the frequency of El Niño/Southern Oscillation (ENSO) events (Quinn and Neal, Chapter 32). Obviously, in understanding the last hundred or so years of climatic variations we also need to consider anthropogenic changes of greenhouse gas concentrations in the atmosphere.

The evidence for solar activity changes was assessed using the variations of ^{14}C in tree rings.

Stuiver and Braziunas (Chapter 30) show that ^{14}C variation can be used as a proxy for solar irradiance change. Their analysis reveals significant periodicities of about 416, 215, 143 and 85 years. Since 1500 the most important variation of solar irradiance was probably related to the Maunder Minimum period between 1645 and 1715. During this interval there were almost no sunspots. This compares with an average sunspot number of 51 over the period 1880 to 1965. Stuiver and Braziunas, estimate that the maximum change of global mean temperatures due to the reduction in sunspot numbers is 0.12°C. This is fairly small given that global mean temperatures have increased by 0.45°C since 1880 (Jones and Bradley, Chapter 13). Evidence for any major climatic change during the 1645 to 1715 period is equivocal. While cool conditions are generally apparent during the 1690s-1710s, warmth is apparent in many regions during other decades of the Maunder Minimum, particularly the 1650s. At present it is not possible to relate historical climatic variations to changes in solar variability with any confidence.

Evidence for changes in the frequency of explosive volcanic events is discussed by Bradley and Jones (Chapter 31). It is apparent that the record of explosive eruptions is quite incomplete, particularly the chemical characteristics of volcanic events. Several different catalogs are in agreement on which were the largest eruptions of the last 150-200 years, but prior to that there is considerable uncertainty about the magnitude and timing of eruption events. It is telling that almost all of the mid and high latitude eruptions in the Northern Hemisphere that we know about before 1900 are in Japan or Iceland where studies are most complete. No doubt many Alaskan, Kamchatkan and Aleutian eruptions remain undocumented. The Southern Hemisphere volcanic chronology is similarly flawed. In view of the many studies which show unequivocal relationships between surface air temperature and certain major explosive eruptions, the importance of a more complete chronology of eruption events can not be over-emphasised; it is an essential pre-requisite to a better understanding of the variability of climate over the last few centuries.

It has only recently been shown that changes in the frequency of ENSO events can have global ramifications (see for example, Bradley *et al.*, 1987b; Ropelewski and Halpert, 1987; Diaz and Kiladis, 1989; Jones, 1989). Particularly in the Tropics, large-scale temperature and precipitation anomalies are often related to the phase and magnitude of the ENSO event. Quinn and Neal (Chapter 32) have produced an historical record of El Niño events back to the beginning of the 16th century. Since 1525 there have been 84 medium to very severe events with an average recurrence interval of 5.5 years. The period since 1925 has had slightly fewer events than the long-term average with events occurring every 6.3 years. Strong El Niños recur about every 9 years. Certain periods stand out because of a lack, or an excess, of events. For example, between 1846 and 1863 there were no severe events. Periods with a higher frequency of events like 1976-87 were 1539-78, 1600-24, 1701-28, 1812-32, 1864-91, 1897-1919 and 1925-1932. These intervals should be focused upon in future research to determine the larger scale significance of periods with above or below average ENSO frequency. It is also important to determine the relative significance of ENSOs when coincident with major volcanic eruptions, as in 1982 (El Chichon) (cf. Handler, 1984).

33.5 The "Little Ice Age"

The term "Little Ice Age" has been used frequently in this volume without any discussion of what the term means. The term originated with Matthes (1939) who stated,

> *We are living in an epoch of renewed but moderate glaciation – a "little ice age" that already has lasted about 4,000 years.*

Thus, in its original useage the term was informal (not capitalized) and referred to what is now called the period of neoglaciation (Moss, 1951; Porter and Denton, 1967). However, Matthes (1940) also noted that,

> *. . . glacier oscillations of the last few centuries have been among the greatest that have occurred during the 4,000 year period. . . the greatest since the end of the Pleistocene ice age.*

It is this latest and most dramatic episode of neoglaciation to which the term "Little Ice Age" is now generally applied, though there is considerable uncertainty about when this period began (and ended) and what its climatic characteristics were. For example, Porter (1986) indicates that the Little Ice Age began near the end of the Middle Ages at around A.D. 1250 and continued until about 1920, whereas Lamb (1977) confines the Little Ice Age to 1550-1850, with its main phase from 1550-1700. Grove (1988) in her comprehensive treatise on the Little Ice Age, seems to concur with Lamb but does not explicitly define the term. Clearly, if the term is to be useful, it must be universally understood. This is especially important in determining what caused the Little Ice Age; you can not explain something if you do not know what it is! Since the focus of this book is the period which many consider to be within the Little Ice Age, it is appropriate that we evaluate the various records presented to try and shed some light on this confusion.

Early evidence for the occurrence of the Little Ice Age came from Europe (Lamb, 1977). Glaciers tended to be more advanced than at present particularly during the 18th and 19th centuries. For example, a series of pictures from the Grindelwald glacier (Zumbühl, 1980; Messerli *et al.*, 1978) illustrates quite dramatically the advance and retreat of the glacier over the last few hundred years. A variety of glacier evidence from other alpine regions of the world also indicates that many glaciers were extensive in the 19th century and have retreated dramatically over the last century (Grove, 1988; Wood, 1988). However, few regions have the detailed historical documentary records which are available for the European Alps to determine glacier positions over time, particularly before A.D. 1850. In most regions, glacier fluctuations have been dated by ^{14}C and/or lichenometry (often calibrated by ^{14}C). ^{14}C dates in the range of 100 to 500 B.P. often provide non-unique calendar year ages (Stuiver and Pearson, 1986) which create considerable uncertainty in reconstructing glacier positions over this interval (Porter, 1981). Glacier advances are also episodic events which result from cumulative increases in mass balance and the interaction of these changes with each glacier's unique dynamic system. Hence, glacier position changes are not easily ascribed to specific changes in climate. Mass balance changes can be brought about by a variety of climatic perturbations (such as changes in snowfall and/or temperature and/or radiation, etc) (Oerlemans, 1988; 1989).

A more useful approach towards understanding the nature of the Little Ice Age and its cause(s) is to examine continuous climatic and paleoclimatic records from around the world to determine what the principal climatic characteristics were during the last 500 years, and thereby to determine what was so different about climate in the recent past. A survey of data presented in this volume and elsewhere reveals three important facts:

1 The last 500 years have not experienced a monotonously cold Little Ice Age; certain intervals have been colder than others.
2 The coldest periods in one region are often not coincident with those in other regions. There is geographical variability in climatic anomalies.
3 Different seasons may show different anomaly patterns over time. Thus, for example, the historical reconstructions of seasonal temperature anomalies in Switzerland (Pfister, Chapter 6) and in the western U.S.S.R. (Borisenkov, Chapter 9) show distinctly different seasonal time series of past climatic anomalies within each region.

A survey of the longest time series from each area reveals quite distinct temporal patterns of temperature anomalies. In Europe, the 19th century experienced the most widespread negative anomalies, generally from around 1820 to ~1915. In many cases the 17th century was also cold. However, most records indicate relatively warm conditions in the 16th and 18th centuries.

In eastern Asia, the 17th century was the coldest period; the late 18th and early 19th century was also cold, but there is little evidence for persistent low temperatures throughout the 19th century, as in Europe.

North American records show the 19th century was the coldest period. In northern regions, dendroclimatic evidence suggests that the 17th century was also cold, but in many parts of the western U.S. conditions at that time were warmer than in the 20th century.

Southern Hemisphere records are consistent in showing the main period of negative anomalies occurred earlier than in the Northern Hemisphere, with widespread cool conditions in the 16th and 17th centuries. In some records these anomalies continued into the mid-19th century.

These conclusions are obtained by making broad generalisations about diverse records which often represent different seasons and which may not all span the entire 500 year period. Furthermore, proxy evidence tends to highlight variations at higher frequencies. Variations at lower frequencies are much more likely to be obscured by the proxy source itself or by the methods used to produce the reconstruction. Nevertheless, as a first step towards a better understanding of the Little Ice Age we feel that generalisations such as those made here are justifiable. They clearly show that the last 500 years was a period of complex climatic anomalies, the understanding of which is not well-served by the continued use of the term "Little Ice Age" (cf. Landsberg, 1985). The period experienced both warm and cold episodes and these varied in importance geographically. There is no evidence for a world-wide, synchronous and prolonged cold interval to which we can ascribe the term "Little Ice Age". Only a few short cool episodes (lasting sometimes for up to 30 years) appear to have been synchronous on the hemispheric and global scale. These are the decades of the 1590s-1610s, the 1690s-1710s, the 1800s-1810s and the 1880s-1900s. Synchronous warm periods are less evident although the 1650s, 1730s, 1820s and the 1930s and 1940s appear to be the most important. As more research begins to fill in the gaps in our knowledge, a better understanding of the prevailing circulation patterns at these various times should emerge. In the meantime, we suggest that the term "Little Ice Age" be used cautiously.

33.6 Recommendations

In order to improve our understanding of this vital period of climatic history we see three important areas requiring further study.

33.6.1 Improvements in data coverage

It is apparent that any conclusions we can draw about climatic fluctuations in the recent past are constrained by the limited geographical coverage of existing high resolution data sets. Large gaps exist for the Tropics, interior Asia, the Middle East and the southern continents. Each of these areas is likely to have different types of resources with which to expand our knowledge of past climatic variations. For example, tree ring reconstructions can almost certainly provide a greatly expanded perspective on conditions across the vast interior of the Asian continent, from the Ukraine to Kamchatka. Considerably more information can be obtained from tree ring studies in the Southern Hemisphere by both expanding the geographic coverage and by examining the records densitometrically. This relatively new approach should also be applied more widely in the Northern Hemisphere. Significant increases in the amount of verifiable climatic variance in densitometric reconstructions clearly demonstrates that the additional effort in chronology production is worthwhile (Briffa *et al.*, 1990).

Southern and southeast Asia can provide a wealth of historical information, from religious and dynastic archives as well as from colonial records (Dutch, Portuguese, French, Spanish and British). Colonial records pertaining to South America may also be available (in Spanish and Portuguese colonial archives). Spanish missionary records from central America and the southwestern U.S. are another possible source of historical climatic data. Historical records from Australasia and southern Africa cover a shorter interval but are worthy of scrutiny (e.g. Vogel, 1989; Nicholls, 1989). North African and Middle Eastern sources should also provide valuable records. The historical data banks that are being developed in Switzerland (Pfister, Chapter 6) and Japan (Murata, Chapter 12) are important. As new information becomes available it can be routinely added, allowing for easy and objective re-evaluations. Material which is later found to be dubious or of non-contemporary origin can be removed. Extension of the techniques outlined in Chapter 6 should be made to other regions of the world where long written histories are known to exist.

Additional approaches to high resolution paleoclimatic reconstruction include studies of varved sediments, and studies of the chemistry and density of growth bands in corals. At present, the value of coral growth increments as a paleoclimatic proxy is somewhat equivocal. Claims of strong relationships between climate and growth bands (e.g. Isdale, 1984) may be premature as recent research has shown the complexity of the problem (Lough and Barnes, 1990a). Nevertheless, there is potential here for valuable (indeed unique) data to be obtained concerning low latitude climate conditions (Lough and Barnes, 1990b; Cole and Fairbanks, 1990).

Studies of varved lake sediments have a long history, yet they have received scant attention in terms of high resolution paleoclimatic reconstruction (O'Sullivan, 1983). Recent studies in Europe (e.g. Zolitschka, 1989) demonstrate their extraordinary potential. Varved lake sediments can be found in many different parts of the world and may provide data from regions where no other proxies exist (e.g. Halfman and Johnson, 1988). Varved sediments may also be found in certain ocean basins where upwelling occurs (e.g. the Santa Barbara Basin, off southern California; Soutar and Crill, 1977; Baumgartner, 1987; the Cariaco Basin off Venezuela; Overpeck *et al.*, 1989). Sedimentary records from these regions may be related to the prevailing circulation regime. Further research on varved sediments, wherever they are found, is strongly recommended.

Eventually, if data coverage can be improved enough, it should be possible to construct large-scale maps of climatic conditions for selected intervals of time (cf Figure 14.2 in Fritts and Shao, Chapter 14). These may still be seasonally specific, but even so they could provide insight into the prevailing larger scale general circulation. For example, it would be of considerable interest to construct a series of maps of climatic anomalies spanning the early part of the nineteenth century when conditions appear to have been quite anomalous in many parts of the world (cf. Figure 19.13 in Briffa and Schweingruber, Chapter 19). It has often been argued that these conditions relate to one or more major explosive eruptions during this time. However, there is evidence that cold conditions may have prevailed *before* the largest eruption of the millennium (Tambora, 1815) and that the Tambora eruption merely accentuated the unusual conditions (Harington, 1991). The occurrence of severe El Niños around this period also complicates the issue. A year-by-year reconstruction of the interval would help to clarify the relationship between volcanic eruptions, ENSO events and climate during this time interval and also shed light on larger scale teleconnections within the climate system.

33.6.2 Improvements in the record of climate forcing factors

Although the record of ENSO events over the last 500 years is now fairly well-resolved (Quinn and Neal, Chapter 32) other factors likely to perturb the climate system are far less well known. Of most significance in this regard is the record of explosive eruptions, particularly the nature and quantity of volatile emmissions produced. This is of critical importance to a better understanding of climate variability over the last few hundred years. Even with an incomplete historical record, it is apparent that the 20th century has experienced far fewer eruptions than earlier centuries. Our knowledge of the number, magnitude, geographic distribution and chemical characteristics of explosive eruptions is increasingly incomplete as we go back in time. Further geological, glaciological, historical and dendroclimatic research is needed to improve the record of climatically significant explosive eruptions.

33.6.3 Improvements in calibration and interpretation

The value of many proxy records could be improved if there was a better understanding of the climatic signal which the record contains. Often the interpretation is constrained by a lack of information for the recent period with which to calibrate the proxy record. For example, the ice core records from Mount Logan, Yukon and Quelccaya, Peru are remote from locations where contemporary climatic records have been kept. If on-site measurements were available, a better understanding could be obtained of what the isotopic and other records in the ice cores represent. Similarly, varved sediment records are often difficult to interpret in climatic terms because long-term limnological and hydrological data are not available. Coral studies are also constrained by the inadequacy of oceanographic data which may be relevant to paleoclimatic interpretations of coral growth and geochemical records. An expansion of environmental measurements, focused on the calibration of specific paleoclimatic proxies, would go a long way towards improving confidence in the past record of climate from environmental archives.

33.7 Conclusions

It is apparent from this volume that we already know a great deal about the climate of the last few hundred years. Many thoughtful and creative approaches have been used to extract information about past climates from obscure and obdurate sources. Nevertheless, there is much that we do not know and much that remains to be done before a clear picture of global climatic variations and their causes will be available. We hope that this book has generated new ideas for resolving the many questions which remain, and that it will spur new and innovative approaches to resolving the climatic record of the last 500 years.

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