PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Relevance of Medieval, Egyptian and American Dates to the Study of Climatic and Radiocarbon Variability [and Discussion]

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Relevance of medieval, Egyptian and American dates to the study of climatic and radiocarbon variability

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Basic radiocarbon dating and dendrochronology have been combined to yield calibrated dates that are more accurate than conventional radiocarbon dates. This has been shown to be true for medieval and Egyptian dynastic dating. Because radiocarbon is a cosmogenically produced radioisotope, heliomagnetic and geomagnetic fields play a major role in its synthesis in the Earth's upper atmosphere. Inasmuch as a calibrated radiocarbon record exists for nearly 10000 years, we now seem to possess in the short-time variations of the production rate a history of solar activity expressed via heliomagnetic fields carried by the solar wind. In turn, solar activity has a controlling effect on climate on Earth within modifications provided by the complex interactions of the atmosphere–Earth–ocean system. Both radiocarbon measurements and other empirical research methods agree on variations of climate during historically more recent periods on Earth. This leads to the suggestion that the radiocarbon calibration curve may be also a significant indicator or tracer for climatic changes for the Holocene or the Neolithic–Mesolithic.

Introduction

Historical dates and the classic chronological frameworks derived from them have been based typically on the interpretation of written records of known languages. However, with the advent of tree-ring dating chronologies could be extended much further into the past, covering now most of the Holocene or Neolithic–Mesolithic in certain parts of the world where dendrochronologic master chronologies were applicable. Careful comparison of historical and dendro-dates confirm their near equivalence thus lending confidence to this biological method based on seasonality.

Dendrochronology not only yields dates synonymous with historical ones, but provides also known-age wood samples that can be radiocarbon-dated. These samples are equivalent to historically well-dated organic materials such as timbers from known-age buildings or straw used in the manufacture of Egyptian mud-bricks. Hence radiocarbon dates can be calibrated to match historical time by either dendrochronologically accurately dated specimen or those whose historic age is well documented.

Today a long and continuous tree-ring calibration for radiocarbon dates is available beginning with the pioneering work of Suess (1965). Since then this has been refined and expanded for most of the past 10000 years by many researchers whose work is collected in the Calibration Issue of *Radiocarbon* (Kra 1986; Becker & Kromer 1986; De Jong *et al.* 1986; Kromer *et al.* 1986; Linick *et al.* 1986; Pearson *et al.* 1986; Pearson & Stuiver 1986; Stuiver & Becker 1986; Stuiver *et al.* 1986; Stuiver & Pearson 1986; Stuiver *et al.* 1986; Stuiver &

Reimer 1986; Vogel *et al.* 1986). Aside from the chronologic aspects this sequence provides as well for a continuous record of secular variations of cosmogenic radiocarbon production.

It has been pointed out by several authors such as Stuiver (1961), Suess (1968) and Damon (1968) that there exists a complex correlation between (1) radiocarbon production trends in the atmosphere based on the interaction of cosmic rays with atmospheric nitrogen, (2) modulation of the cosmic ray flux by helio- and geomagnetic fields and (3) solar activity that controls both heliomagnetic activity and in the end terrestrial climates. In essence, higher solar energy output at the time of sunspot maxima as reported on recently by Willson & Hudson (1988) translates to stronger heliomagnetic fields that interfere more with access of cosmic rays into the Earth's atmosphere. This scenario would result in lower radiocarbon production with concomitant lower levels of incorporation into the biosphere such as tree-rings. At the same time increased insolation of the Earth's surface would result in a warming trend. Conversely, lower solar energy levels would tend to increase radiocarbon nucleosynthesis as weaker heliomagnetic fields deflect fewer cosmic rays while the Earth as a whole experiences cooling. These reaction steps do not take into account the ameliorating effects of the oceans and other reservoirs that significantly affect these relations, but whose joint action do not seem to completely mask them. Thus radiocarbon measurements not only yield dates but also seem to provide climatic information.

Radiocarbon dates from the Middle Ages

Before the extensive isotopic tree-ring studies summarized in the Calibration Issue of *Radiocarbon*, the veracity of Suess's (1965) secular variations was checked by dating known-age buildings of medieval vintage located principally in England and France as discussed by Berger (1970*a*, 1985) and Horn (1970). Indeed their correct historical ages could only be calculated from radiocarbon ages if Suess's calibration was used.

Experimentally, all these timber samples were first analysed for their position within the construction members relative to the outer-most tree-ring to determine the felling date that starts the radiocarbon clock. In the laboratory, 10–15 g of sample were decontaminated with

Table 1. List of known-age measurements from the Middle Ages

UCLA no.	location	in-tree correction/years	$\delta^{13}C$, PDB (‰)	^{14}C age years	historical age (A.D.)	calibrated age[a] (A.D.)
1307	Arpajon	40	−23.83	515 ± 30	1450–1470	1450
1316	Enstone	40	−24.61	630 ± 50	1382	1390
1048	Gt Coxwell	40	−24.92	870 ± 40	1250	1250
1049	Gt Coxwell	15	−25.20	750 ± 30	1250	1245
1309	Maubuisson	10	−22.58	860 ± 40	1236	1050–1220
572	Mereville	20	none	490 ± 40	1456–1472	1440
1304	Mereville	30	−24.69	400 ± 50	1456–1472	1460 or 1600
1312	Milly	none	−22.80	420 ± 45	1479	1450
1313B	Parcay–Meslay	10	−24.52	655 ± 30	1211–1227	1250
570	Parcay–Meslay	none	none	735 ± 50	1211–1227	1225–1250
1310	Questembert	40	−26.02	330 ± 30	1675	1500, 1625–1670
1303	Richelieu	30	−24.54	380 ± 50	1631–1640	1480 or 1600
1306	Sully	100 + ?	−23.04	930 ± 30	1363	1300
1308	Troussures	none	−24.42	400 ± 45	1609	1450 or 1600
1214	Buddha	none	none	820 ± 50	13th century	13th century

[a] For calibration the Suess relation (1965) was used.

dilute, cold hydrochloric acid to remove all inorganic carbonate dust or lichen and moss residue from leaking roofs. After washing and drying samples were burnt in a stream of pure oxygen to carbon dioxide. This gas was then purified by treatment with aqueous silver nitrate to precipitate halogens, hot copper oxide to oxidize any carbon monoxide to dioxide and chromic acid solutions for drying and elimination of impurities. Electronegative contaminants such as traces of oxygen were removed by repeated passage of the gas over elementary copper at 600 °C. The resultant pure carbon dioxide was then assayed after radon decay by repeated counting for at least 1000 min in a 7.5 l proportional counter whose accuracy in this time range is ±25 years. In addition, stable carbon isotope ratios were determined and the standard correction applied to exclude fractionation effects.

The medieval dates obtained are listed in table 1 and show very good correlation between historical and experimental ages once a tree-ring calibration is applied. In some cases alternate radiocarbon ages or age ranges are due to the nature of the fluctuations in the radiocarbon production rate as represented by calibration curves. Thereafter the success of this dating approach was tried on many buildings of uncertain age in continental Europe, England and Ireland as discussed by Berger (1970*a*, 1990) and Horn (1970).

Radiocarbon dating of Egyptian dynasties

Inasmuch as these medieval samples provided verification of the calibration proposed by Suess for the past millennium or so, radiocarbon dating of Egyptian dynastic specimen offered a check by the earliest and best understood historical chronology of subsequent extensions of

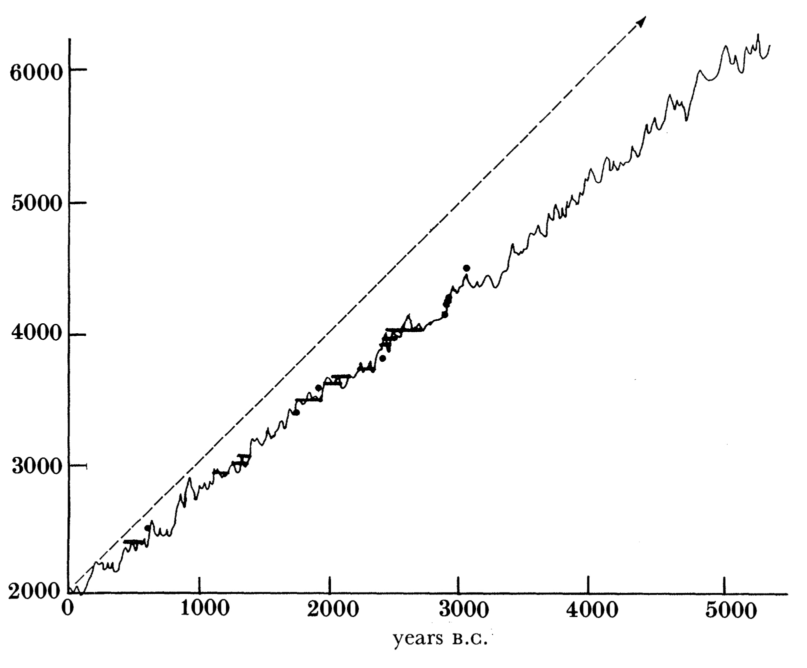

Figure 1. Calibration curve by Suess (1979) showing short-term deviations caused by heliomagnetic activity and long-term change due to geomagnetic effects. Calibrated radiocarbon dates from Egyptian dynastic sites are plotted as lines indicating dating ranges or circles that are specific dates. ----, Relation based on constant atmospheric ^{14}C levels. (After Berger (1985).)

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TABLE 2. LIST OF KNOWN-AGE MEASUREMENTS FROM EGYPT

UCLA no.	location	dynasty	material	$\delta^{13}C$, PDB (‰)	^{14}C age years	approximate historical age (years B.C.)	calibrated age[a] (years B.C.)
1200	Tomb 3357 Sakkara	I	matting	−22.65	4500 ± 60	3100–3000	3030
1201	Tomb 3503 Sakkara	I	matting	−22.36	4290 ± 60	3100–3000	2900
1202	Tomb 3035 Sakkara	I	matting	−21.95	4235 ± 60	3000	2900
1203	Tomb 3505 Sakkara	I	matting	−22.71	4140 ± 60	2890	2900 or 2600
739	Mastaba 2050 Tarkhan	I	linen	none	4265 ± 80	3100–2890	2900
1204	Tomb 3046 Sakkara	II	matting	−23.05	4190 ± 60	2890–2686	2900 or 2600
1205	Tomb 3030 Sakkara	III	matting	−23.36	4055 ± 60	2670	2700–2400
1206	Tomb 3510 Sakkara	III	wood	−25.36	3965 ± 60	2686–2613	2700–2400
1207	Tomb 3075–5 Sakkara	III	matting	−23.12	4050 ± 60	2686–2613	2700–2400
1208	Tomb 3508/10	IV?	linen	−25.62	4015 ± 60	2613–2494	2700–2400
1389	Cheops boat Gizah	IV	grass rope	−11.78	4210 ± 60	2613–2494	2600 or 2900
928	Gizah 2220 Pit B, Gizah	V	linen	none	4120 ± 60	2494–2345	2600 or 2900
1403	Mastaba of Haishetef, Zoser encl.	V-Late I. Inter P.	matting	−22.79	3935 ± 60	2494–2173	2550–2400
1387	Tomb of Mereruka, Teti-Sakkara	VI	matting	−22.47	3860 ± 60	2360	2450–2350
1388	Teti Sakkara	VI	wood	−22.13	3950 ± 60	2360	2550–2400
1413	Gebelin	XI	wood	−25.59	3770 ± 60	2133–1991	2400–2250
1211	Tomb 386 Thebes	XI	wood	−25.36	3500 ± 60	2133–1991	1900–1750
1398	Tomb 386-T	XI–XII	linen	−25.49	3330 ± 60	1991–1786	1700
1399	Tomb 386-I	XI–XII	charcoal	−26.52	3615 ± 60	1991–1786	2100–1950
1400	Tomb 386-T	XI–XII	wood	−25.25	3700 ± 60	1991–1786	2200–2000
1212	Sesostris II Pyramid, El-Lahun	XII	matting	−10.00	3500 ± 60	1991–1786	1900–1750
900	Sesostris III Funerary boat	XII	wood	−25.10	3640 ± 60	1991–1786	1800
1390	Ramesses II Funerary temple	XIX	matting	−11.42	3075 ± 60	1320–1200	1400–1300
1393	Tomb 158 Thebes	XIX–XX	matting	−11.27	3060 ± 60	1320–1085	1400–1300
1394	Tomb 158 Thebes	XIX–XX	wood	−24.02	3030 ± 60	1320–1085	1400–1300
1395	Tomb 283 Thebes	XIX–XX	wood	−25.19	2880 ± 60	1320–1085	1200–1100
1401	Tomb 386 Thebes	XXVI	wood	−24.96	2515 ± 50	664–525	600
1391	Tomb 34 Thebes	XXV–XXVI	matting	−11.15	2530 ± 60	751–525	600
1397	Gt Temple of Amun, Karnak	XXX	matting	−11.75	2335 ± 60	380–343	600–400

[a] For tree-ring calibration Suess's (1979) correlations was used.

calibrated dating. The best historically dated and geochemically most-suited samples were collected with the cooperation of I. E. S. Edwards, British Museum, W. B. Emery, University College, London, W. F. Libby, UCLA, and G. T. Martin, Corpus Christi College, Cambridge. Most of the sample material consisted of plants growing only a single or few seasons such as straw, reed or flax.

All samples were decontaminated in this laboratory after treatment with dilute hydrochloric acid followed by sodium hydroxide leaching to remove humic acids from the archaeological environment below ground level. Conversion to carbon dioxide was identical to the method used before. Moreover, the same dating and correction procedures were used. The results of this measurement programme are listed in table 2 below. They were discussed earlier by Berger (1970*a*, 1985) in the light of the slowly emerging calibration curves.

As evident from this list, calibration of Egyptian radiocarbon dates by Suess's extended correlation and other subsequent calibrations results in dates closely resembling the historical estimates except that there occur occasionally ranges of time or alternate dating possibilities that need to be resolved by other methods.

In general Suess's calibration over the past several thousand years is very similar to those reported on in the Calibration Issue. Yet a unified standard calibration curve needs yet to be devised and agreed upon by the world's radiocarbon research community.

Solar activity, climate and radiocarbon variations

Recent observations by Willson & Hudson (1988) of solar activity changes during solar cycle 21 with the Active Cavity Radiometer Irradiance Monitor (ACRIM I) on board the *Solar Maximum Mission* (*SMM*) satellite have provided a virtually continuous record of total solar irradiance. Long-term variations during a downward trend and subsequent upturn of the sunspot cycle suggest a direct correlation between luminosity and sunspot populations. At its peak the Sun was 0.1 % brighter than at its minimum. A model of solar luminosity modulation by magnetic activity between 1954 and 1984 as discussed by Lean & Foukal (1988) is successful in matching slow variations of solar irradiance measured simultaneously from the *Nimbus*-7 and *SMM* satellites. In fact this model extending back over three 11-year solar cycles predicts that the Sun is always brighter at activity maximum than at minimum.

The distribution of solar energy radiated is illustrated in figure 2, which shows that ultraviolet, visible and infrared radiation together account for virtually 100 % of solar luminosity. The energy of the corpuscular radiation emanating from the Sun as solar wind amounts to only about 10^{-6} of total solar output. Major differences in temperature of the terrestrial atmosphere during sunspot maximum and minimum are illustrated in figure 3 demonstrating a large effect at altitudes in excess of 100 km and reaching a full 30 % increase above 300 km. Near the surface of the Earth the differences are very small numerically yet large enough to influence climate.

The most comprehensive collection of empirical climatic observations has been assembled by Lamb (1977). Recently a more specialized and very extensive summary of the 'Little Ice Age' has been published by Grove (1988). In 1983 Leona Libby summarized our understanding of what was then known about the interrelation between climate, stable isotopes and historical economic trends (figure 4). La Marche (1974) related the departure of tree-ring widths of bristlecone pine (*Pinus longaeva*) in the White Mountains of California to precipitation and also

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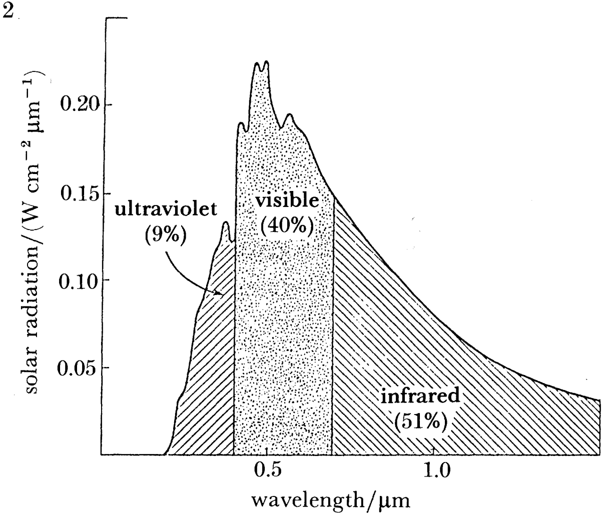

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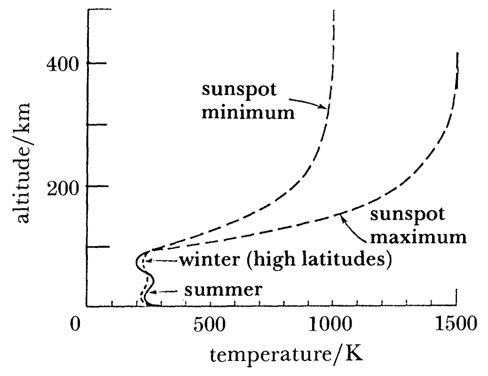

FIGURE 2. Distribution of solar energy between ultraviolet, visible and infrared radiation. (After Glasstone (1965).)

FIGURE 3. Response of the atmosphere to solar activity at sunspot minimum and maximum. (After Glasstone (1965).)

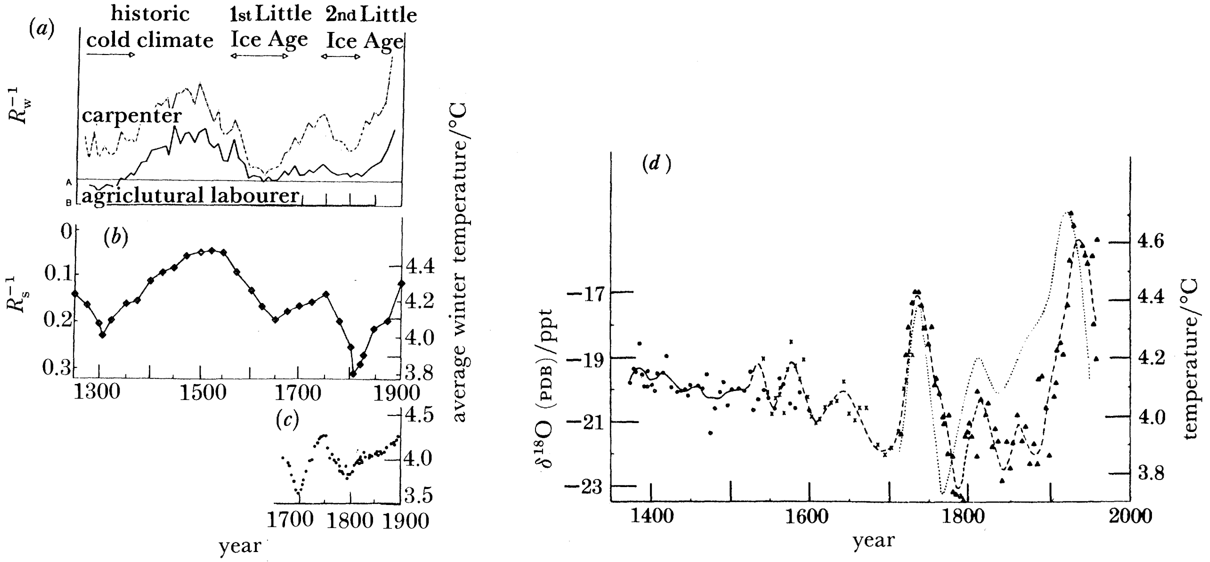

FIGURE 4. Correlation between economic data, climate and oxygen isotopic data for England and Central Europe (after Libby (1983)). (*a*) The amount of wheat purchaseable in England with the daily wages of a carpenter and a farmhand. (*b*) The price of wheat in central England (black diamonds). (*c*) A short curve to A.D. 1650 illustrating the average winter temperature in central England. (*d*) Oxygen isotopic data for oaks from central Germany. Spessart oak 1: ▲, 7 sample (30 year) running average; ---, smoothed by eye. Spessart oak 2: ×, 5 sample (30 year) running average. Marburg oak: ——, 5 sample (30 year) running average; ●, 4–7 year sample; ·····, average January, February and March temperatures in England. All curves show a minimum at A.D. 1800 and further substantial agreement in the latter part of the sixteenth century, periods having been called Little Ice Ages.

temperature anomalies represented by local glacial advances. A broader comparison by Suess (1968) included sunspot numbers, variations of the specific activity of radiocarbon in wood, mean-temperatures in England and winter severity indices for Europe over the past 1000 years (figure 5). A much longer correlation covering several millennia is possible today because a longer tree-ring calibrated radiocarbon record is available coupled with a much more extensive history of glacial advances and retreats. In a world-wide survey Röthlisberger (1986) published a remarkable comparison of glacial responses on nearly every continent. Apparently, glaciers behave very similarly world-wide in their reaction to major climatic changes leading to the belief that they really represent global climatic effects.

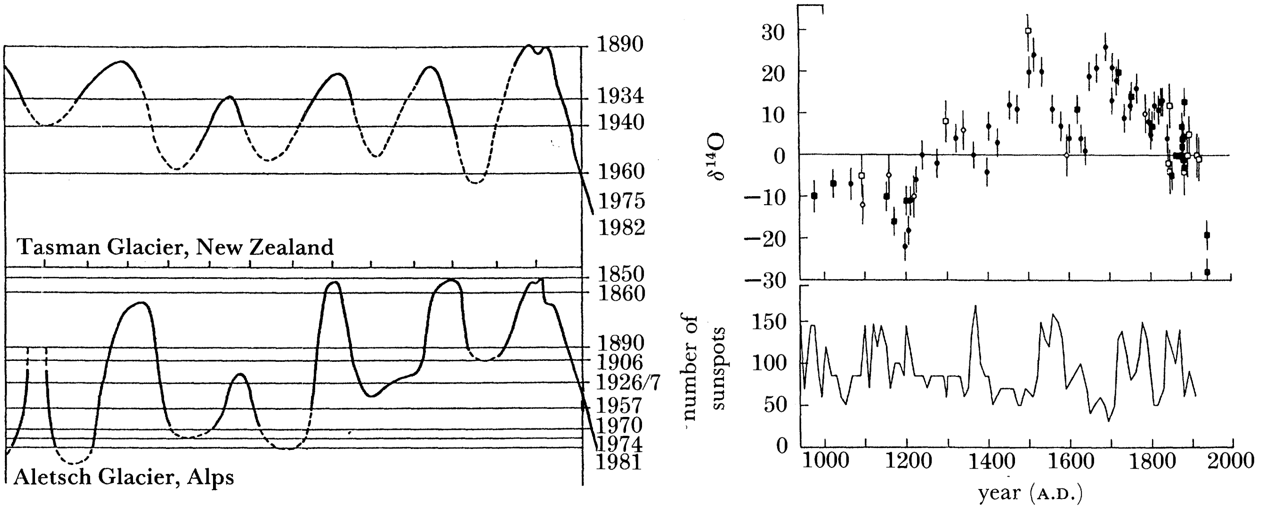

FIGURE 5. Comparison of solar activity expressed by sunspot number (Schove 1955), variations in the radiocarbon levels of wood (Suess 1965) and fluctuations of the Tasman glacier, New Zealand and the Grosser Aletsch glacier, Alps as combined in Grove (1988). Low sunspot number conditions and high radiocarbon production go hand in hand with glacier retreats.

A comparison of these glacial fluctuations with secular changes in cosmogenic radiocarbon production adapted from Neftel *et al.* (1981) is presented below in figure 6. Inspection suggests a sense relation between glacial advances and higher than average radiocarbon production. On the other hand, glacial retreats occur at times when radiocarbon synthesis is inhibited by reduced cosmic ray flux caused by increased solar activity. Thus the operation of the natural processes involved can be characterized as follows: when the Sun is more active it increases insolation on Earth, yet shields it more effectively from cosmic rays by stronger heliomagnetic fields. This leads to a reduction in radiocarbon production and subsequent lower specific activity levels in the terrestrial biosphere. Conversely, during periods of minimum solar activity, a cooler Earth–atmosphere system is exposed to higher concentrations of radiocarbon. As a consequence radiocarbon production trends seem to be able to serve as an indicator or tracer of climatic variability on the Earth. Because the tree-ring calibration record is continuously being extended toward the Holocene–Pleistocene boundary we have now already a climatic indicator chart covering most of the Neolithic and Mesolithic. In fact it should be possible to test its validity if climatic excursions are known to exist in certain prehistoric time intervals.

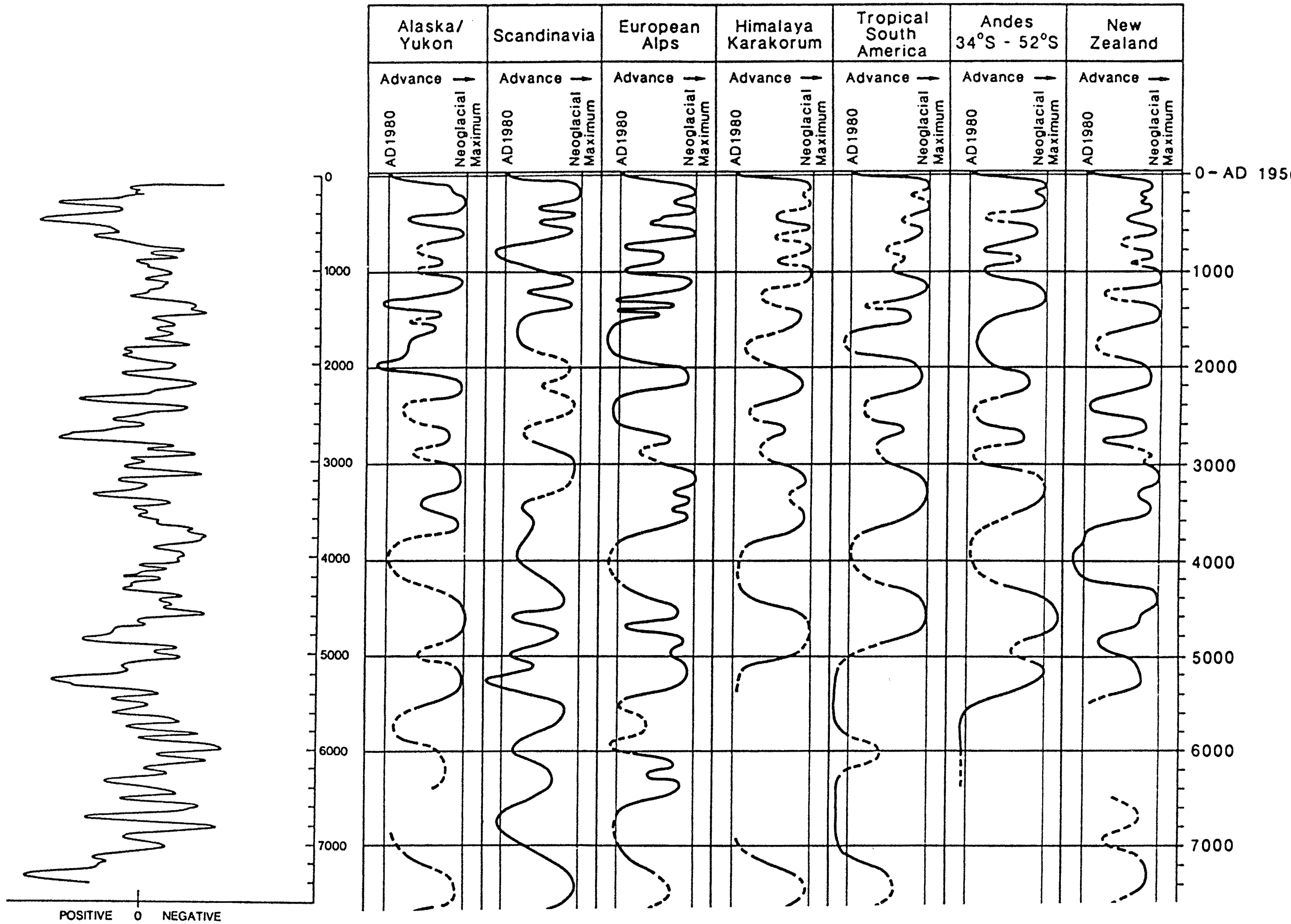

FIGURE 6. Comparison of world-wide glacial responses (Röthlisberger 1986) with radiocarbon production variations (Neftel *et al.* 1981). Positive radiocarbon production occurs at times of glacial advance signalling a cooling climate. Negative radiocarbon production trends indicates greater solar activity and glacial retreat, i.e. warming climate.

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Radiocarbon dates from the American southwest

This region is one of the most intensively investigated archaeologically in the United States. There are thousands of radiocarbon dates available, typically published in *Radiocarbon*, that concern human and climatic activity. The first study to test the use of the radiocarbon calibration as a climatic tracer involves timberlines. They respond to changes in climate by moving up or down mountains to accommodate the best environment in which particular tree species will grow. Typically, a warming trend will cause trees to move higher on mountain ranges in terms of new tree generations they produce. Cooling will induce the reverse effect, the upper tree line will gradually recede downward until a new environmental–biological equilibrium has been established.

The first study of a timberline advance to higher elevations in the White Mountains of California and the nearby Snake Range, Nevada, in itself signals a warming trend that has been observed in the southwest and called the Altithermal. A discussion of post-glacial climate and archaeology is found in a publication by Baumhoff & Heizer (1965), which addresses specifically the American desert West. Samples for this timberline study were collected by La Marche & Mooney (1967) and most radiocarbon dated at UCLA. All specimens were treated for the removal of contamination as before.

The data (table 3) show a subalpine forest advance of bristlecone pines upward of the order of 120–150 m. When the probable dates for the establishment for these trees are inspected, they often fall into date ranges because the basic radiocarbon dates need calibration, which then results in time ranges. However, when these ranges are compared to the isotopic curve in figure 5, and fitted into the glacier reaction curves, the probable date of first establishment of the trees can perhaps be further refined. In general the data agree well with the concept of the Altithermal, Climatic Optimum or Hysithermal first suggested by Antevs (1948).

Table 3. Age and altitude of bristlecone pines

UCLA no.	location	altitude sealevel/m	above tree-line/m	in-tree correct/years	^{14}C age years	calibration age[a]/(years BP)	tree start (years BP)
1070F	White Mtns	3480	120	2260	840 ± 80	850	3110
1070B	White Mtns	2490	130	660	2540 ± 80	2550–2850	3210–3510
1070G	White Mtns	3510	150	735	3565 ± 80	3750–4050	4485–4785
1070A	White Mtns	3360	120	507	4000 ± 80	4400–4850	4907–5357
1070C	Snake Range	3540	120	138	2350 ± 80	2400–2750	2538–2888
1070D	Snake Range	3540	120	809	2240 ± 80	2150–2350	2559–3159
LJ-1336	Snake Range	3540	120	87	3930 ± 80	4200–4450	4287–4587

[a] For calibration the Suess relation (1965) was used because this is also the base for the correlation in figure 4. LJ-1336 was determined in the La Jolla laboratory of Suess.

A later and more extensive study recognizes upward tree-line motion by as much as +200 m coupled with a temperature increase of about 2 °C above today's July average as noted by La Marche (1973). The same study also notes a dramatic decline of the timberline at the beginning of the Little Ice Age around A.D. 1500.

Another study covers the entire Mohave Desert, which is principally located in California. This work is based on the radiocarbon dating of packrat (Neotoma) middens that are made from collections of plants in the limited foraging area of these animals. Botanical analysis permits determination of the plant species used and therefore archaeoclimatic evaluation as discussed by Wells & Berger (1967). A large geographic area was analysed confirming the existence of woodland where today remain only disjunct stands of trees in the higher elevations separated below by desert. More than 20 UCLA radiocarbon dates ranging from about 8000 to more than 40000 years indicate how xerophilous juniper-dominated woodland descended some 600 m below the present lower limit of woodland during the waning millennia of the Pleistocene. The overall data show a slow spreading of the desert from what is now Sonora northward into California and adjacent states. Because, unfortunately, the radiocarbon calibration curves do not yet reach significantly into this time range, no correlations are possible. It goes without saying that the transition period from the Pleistocene to the Holocene is one of the most interesting in terms of the isotopic response to a major change in insolation and attendant environmental effects.

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Discussion

J.-C. Pecker (*Collège de France, Paris, France*). I would like to draw attention to a study by F. Link, a few decades ago, of medieval and antiquity records. This study was very thorough, and has concerned astronomical observations of auroras, novae, planets, etc. It strongly suggests a period of 300–400 years in the atmospheric transparency, this being an indication, according to Link, of a 300–400-year period in the solar activity. I think that one should not evoke that kind of problem without paying due tribute to the pioneering work of the late F. Link.

R. Berger. This is a very interesting comment in the light of recent work by Sonett & Suess (1984) and Sonett (1984), who discuss long-term periods in bristlecone pine ring-widths and atmospheric radiocarbon variations as well as very long solar periods and the radiocarbon record respectively.

Additional references

Sonett, C. P. 1984 *Rev. Geophys. Space Phys.* **22**, 239.
Sonett, C. P. & Suess, H. E. 1984 *Nature, Lond.* **307** 141.

J. M. Grove (*Girton College, Cambridge, U.K.*). The diagram of climatic change for Scandinavia by Ahlmann is now completely out of date. It shows no cool phases during the Holocene (Röthlisberger 1986). There is now extensive evidence that the Little Ice Age was a global phenomenon, this pointing to a fall in global temperature, though with some complication in timing and regional impact (Grove 1988).

R. Berger. The diagram by Ahlmann was shown during the oral presentation as a historical and scientific illustration of interest in the Little Ice Age. In this publication reference is made to Röthlisberger's work and your own massive compilation of data that are much more up to date.