Radiocarbon Record of Solar Variability and Holocene Climatic Change in Coastal Southern California

Owen K. Davis, John Jirikowic, and Robert M. Kalin

Abstract: The tree-ring calibration of radiocarbon dates may provide a chronology for high-frequency global climatic change. Large (~10 parts per mil) Δ-^{14}C excursions in tree-ring series from North America, Great Britain, and Germany are associated with brief, intense cold periods throughout the Holocene. The coincidence of cold periods and Δ-^{14}C anomalies first was suggested by deVries (1958) for the Little Ice Age. Schmidt and Gruhle (1988) have combined dendrochronologic analysis and radiocarbon dating to demonstrate coincident cool/wet climate and increased ^{14}C production during the Homeric (880-600 BC) and Greek (460-260 BC) minima. Many sites in western North America record cold/wet climate at this time. Pollen analysis and 5 radiocarbon dates for a 687-cm core provide a detailed chronology of environmental change for San Joaquin Marsh at the head of Newport Bay, Orange County, California. Sediment deposition kept pace with sea level rise during the mid-Holocene, but after 4500 years BP, sea water regularly reached the coring site, and salt marsh was the local vegetation. Brief periods of dominance by fresh-water vegetation 3800, 2800, 2300 and after 560 years BP correlate global cooling events and (except the 3800-year BP event) with ^{14}C production anomalies. The coincidence of climate change and ^{14}C anomalies support a causal connection with solar variability, but regardless of the causal mechanism(s) the Δ-^{14}C curves provide a chronology for global, high-frequency climatic change comparable to that of Milankovitch cyclicity for longer time scales.

Basis of Radiocarbon Dating

Since its inception in the 1950s (Libby 1955), radiocarbon dating has been the primary method for dating late Pleistocene and Holocene environmental change. A basic tenet of this technique is that the ratio of ^{14}C/^{12}C and, therefore, the production of the ^{14}C has remained nearly constant through time. Unstable ^{14}C isotopes are produced by the ^{14}N(n,p)^{14}C reaction in the upper atmosphere, resulting from cosmic ray bombardment. Libby's (1955) preliminary analyses indicated production of ^{14}C was nearly constant. Subsequent studies have shown a pattern of exceptions to constant formation.

Tree-Ring Calibration of Radiocarbon Dates

The most detailed examination of changes in the ^{14}C/^{12}C ratio has come from painstaking radiocarbon dating of tree rings (Stuiver and Pearson 1986; Pearson and Stuiver 1986; Pearson *et al* 1986; Linick *et al* 1985; Stuiver *et al* 1986; Kromer *et al* 1986; Linick *et al* 1986). Carefully aged tree-ring samples are ^{14}C dated in 20-year, 10-year, or smaller increments. These meticulous studies, beginning with deVries (1958), show

---

In K.T. Redmond, Editor, 1992. Proceedings of the Eighth Annual Pacific Climate (PACLIM) Workshop, March 10-13, 1991: California Department of Water Resources, Interagency Ecological Studies Program Technical Report 31.

the $^{14}C/^{12}C$ ratio has varied through time and also show the effects of atomic bomb testing (^{14}C dates too young), the industrial revolution (^{14}C dates too old), and earlier fluctuations in the $^{14}C/^{12}C$ ratio. Prior to the industrial revolution, radiocarbon dates are older than tree-ring ages from 700-2400 years BP (^{14}C years Before Present) and younger than tree-ring ages in samples older than 2400 years BP. The ^{14}C fluctuations are global in extent, and the Δ-^{14}C curves have been reproduced for western North America, Great Britain, and Germany (Stuiver and Kra 1986).

Causes of Radiocarbon Anomalies

Several factors affect the $^{14}C/^{12}C$ ratio, on a variety of time-scales (Damon *et al* 1978). The atmospheric concentration of CO_2 is known to vary from 200 to 300 ppmv during glacial/interglacial climatic cycles (Neftel *et al* 1982; Barnola *et al* 1987; Genthon *et al* 1987) and to vary by 20 ppmv on an annual basis (Keeling *et al* 1989). Both global biomass fluctuations and changes in oceanic circulation have been implicated in atmospheric CO_2 oscillations. Because ^{12}C is by far the more abundant isotope, the $^{14}C/^{12}C$ ratio is less sensitive to CO_2 fluctuations in the atmosphere than to changes in ^{14}C production.

The production of ^{14}C is modulated by effects of Earth's magnetic field and by the solar wind on the rate of cosmic ray bombardment of nitrogen. A strong geomagnetic field deflects cosmic rays and, therefore, reduces the rate of ^{14}C production. Geomagnetic modulation probably is responsible for the long-term (tens of millennia) deviation of ^{14}C dates from tree-ring ages. Stuiver *et al* (1991) suggested it also could be responsible for fluctuations on shorter (millennium) time scales.

A strong solar wind (*ie*, an active sun) also may deflect cosmic rays and decrease ^{14}C production. Solar activity typically is implicated in high-frequency (century to decade) changes in the $^{14}C/^{12}C$ ratio (Stuiver and Braziunas 1988). The timing and magnitude of the Δ-^{14}C fluctuations match the record of cosmogenic ^{10}Be in ice cores at high frequencies (Beer *et al* 1988), so solar forcing is supported.

Periodicity of Radiocarbon Anomalies and Climatic Change

Stuiver and Braziunas (1988) and Hood and Jirikowic (1990) have shown that the high-frequency (century) ^{14}C cycles are similar to one another. Figure 1 shows correlation of Δ-^{14}C values to those of the 2850-2650 BC anomaly (the "Homeric Minimum"; see below). Note that groups of peak correlations (p>95%) recur at 2000-3000 year intervals. The pattern formed by the ^{14}C anomalies is commonly referred to as "Suess wiggles", and the periodicities of these variations is close to that of sunspot cycles: the 200-year cycle (Schove 1955, 1980), the 88-year Gleissberg cycle

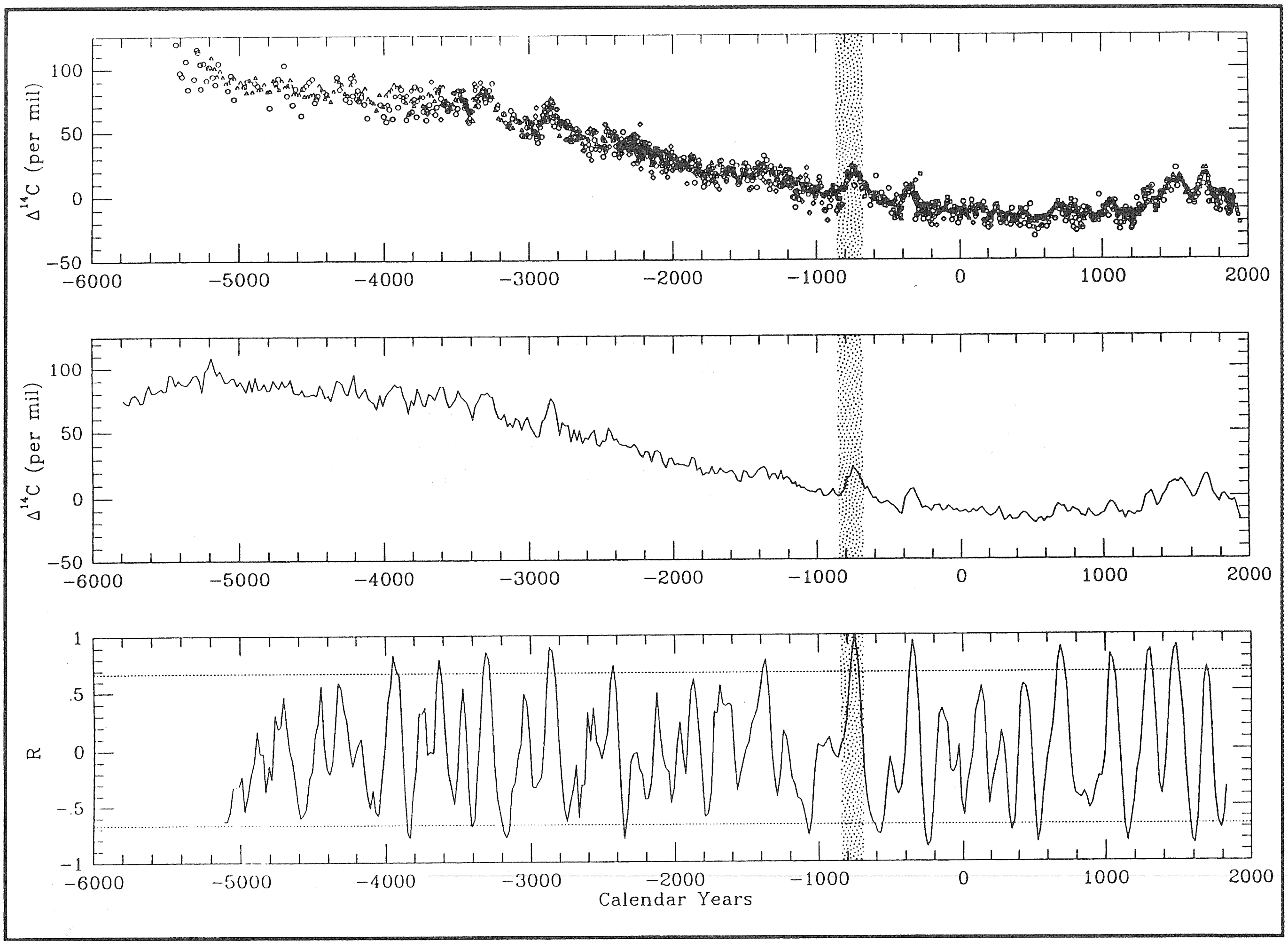

Figure 1. Correlation of Δ-^{14}C anomalies to the Homeric Minimum.
A. Raw Δ-^{14}C determinations. Symbol shapes indicate geographic origin of tree-ring samples: Circle=Suess (1978), Box=Stuiver and Becker (1986), Triangle=Pearson and Stuiver (1986), Solid Box=Linick *et al* (1985).
B. Raw data smoothed by 10-year Gaussian average.
C. Pearson correlation of a moving 200-year window to 200-year interval during the Homeric Minimum (shaded).

Table 1
Periodicities Resulting from Spectral Analysis of the Tree-Ring Calibration of ^{14}C Dates and Spectral Analysis of Ice Cores and Lake Cores

	RADIOCARBON					ICE CORE	LAKE SEDIMENTS	
Sunspot Cycle Names	Sonett 1990 MEM	Sonett 1990 DFT	Stuiver et al 1991	Damon & Linick 1986	Houtermans et al 1971	Dansgaard et al 1984	Halfman et al 1988	Anderson 1991
				11,300				
	2241	**2272**	**2014**	**2400**	**2350**	**2000**		
				1200	1300			
	805	909-649	951-720	800				
	504		512		600	540		
	385		444		420			
	232		229				280	
	208	**207**	**208**		**210**	**181**	**195**	**200**
		149	155-147				160	
			130-123	100			98	
Gleissberg	**88**	**88**	**88**	**80**		**78**	**78**	
								50-40
Hale								22
Schwabe			11					

(Gleissberg 1958), the 22-year Hale cycle (Schove 1980), and the 11-year Schwabe cycle (Povince 1983).

The exact lengths of the radiocarbon cycles vary slightly with the mathematical technique used (Sonett 1990), but certain frequencies (*eg*, 2400, 208, and 88 years) are common to nearly all analyses (Table 1). However, time series analysis by Thomson (1990), indicates the 2400-year cycle is categorically different from the shorter cycles (*ie*, the 208-year cycle).

Climate cycles of lengths similar to those of Δ-^{14}C series support the radiocarbon/climate connection. The 2500-year climatic cycle has been detected in many studies of marine and lacustrine sediment and ice cores (DeDeckker *et al* 1991; Shuti and Yujiang 1990; Pestiaux *et al* 1987; Starkel 1987; Dansgaard *et al* 1984; Schnitker 1982; Benoist *et al* 1982; Pisias 1983; Pisias *et al* 1973). Indeed, 2500 years is the fundamental division of the European Environmental sequence (*ie*, Blytt-Syrnander sequence; Iversen 1973). The 208- and 88-year cycles appear in spectral analysis of varved sediment sequences (Halfman *et al* 1988; Anderson 1991) and in the Greenland ice core 18O/16O record (Dansgaard *et al* 1971).

Documenting the Radiocarbon/Climate Connection

The connection between ^{14}C and climate first was postulated by deVries (1958) and was developed by Suess (1965), Damon (1968), Eddy (1977), and Stuiver (1965). Suess (1965) and deVries (1958) noted the correspondence between reduced ^{14}C production, colder global climate, and reduced solar activity during the Maunder (sunspot) Minimum, AD 1645-1715, when several lines of evidence indicate reduced solar activity by about 0.1% (Eddy 1976; Lean 1991), and global temperature was ~1°C less than today (Grove 1988). During the Maunder and other Little Ice Age sunspot minima (Dalton AD 1805-1835, Sporer AD 1400-1510, and Wolf AD 1290-1350), the radiocarbon content of the atmosphere was ~10 parts per mil greater than background values. Earlier ^{14}C production maxima correlate with Holocene glacial advances (Eddy 1977). However, Lamb (1977, Appendix) and Pittock and Shapiro (1982) note the many failures to use sunspot cycles to forecast climate.

A convincing connection between cool/wet climate and increased ^{14}C production 750-200 BC has been made by Schmidt and Gruhle (1988) using climatic reconstructions from and radiocarbon dating of the same tree-ring series.

Holocene cold periods are difficult to associate conclusively with the brief (100-year) ^{14}C production anomalies due to the relative imprecision of dating for sedimentary sequences. However, the correlation of climate change and ^{14}C production must be tested. Regardless of the causal mechanism(s) (solar, climatic, geomagnetic), the Δ-^{14}C curves provide a chronology for global, high-frequency climatic change. That is, 10 parts per mil Δ-^{14}C excursions are associated with brief, intense cold periods from throughout the Holocene. Complete understanding of the process awaits further theoretical development, but development of explanatory mechanisms must proceed from careful empirical examination of the relationship between ^{14}C fluctuations and climatic change.

Naming ^{14}C Anomalies

Names given to ^{14}C production anomalies are informal and vary among authors, but the names are useful because their ages vary slightly among Δ-^{14}C records and among authors. Although ^{14}C production increases during sunspot minima, the positive anomalies are referred to as "Minima" due to the ^{14}C/sunspot correlation made by Eddy (1977) for the Little Ice Age. Little Ice Age sunspot minima and ^{14}C anomalies are named for solar astronomers, and early Neoglacial ^{14}C production maxima are named for "the general historical period in which the apparent anomaly falls" (Eddy 1977 p. 183).

Eddy simply numbers minima earlier than 1 AD, but Landscheidt (1987) names four of these anomalies: Greek (460-260 BC), Homeric (880-600 BC), Egyptian (1400-1200 BC), and Sumarian (3390-3190 BC) minima. Schmidt and Gruhle (1988) refer to the Homeric and Greek minima together as the Hallstattzeit (705-200 BC) Minimum (= Hallstatt Period or Early Iron Age; Brooks 1949 pp. 337-356). The ^{14}C anomaly 660-770 AD is called the "Medieval Minimum" by Eddy (1977), but Hood and Jirikowic (1990) use the same name for the 940-1140 AD anomaly. The names given to minima in Figure 2 follow Eddy's (1977) precedence; *ie*, Little Ice Age minima are named for astronomers and earlier minima are named for cultural periods and events.

Late Holocene Climate of California

High-resolution chronologies of climate in California generally record cold climate during radiocarbon minima, but certain cold periods lack minima. The analysis of radiolarian assemblages in varved sediments of the Santa Barbara Basin indicate fluctuations of winter (February) sea surface temperature by 12°C with cold periods 3850-3750 (no ^{14}C anomaly), 2830-2550 (Homeric), and 650 (Wolf) years ago (Pisias 1978). In the Campito Mountain tree-ring chronology (LaMarche, 1978), the period 2900-2300 years BP (Homeric) is a cold interval with generally narrow rings. Later, brief periods with very narrow rings occur 1140-1060 (Roman), 560-540 (Sporer), and 340 (Maunder) years BP. Cold climate during the Little Ice Age and Homeric-Greek ^{14}C minima are well represented in the California climate record.

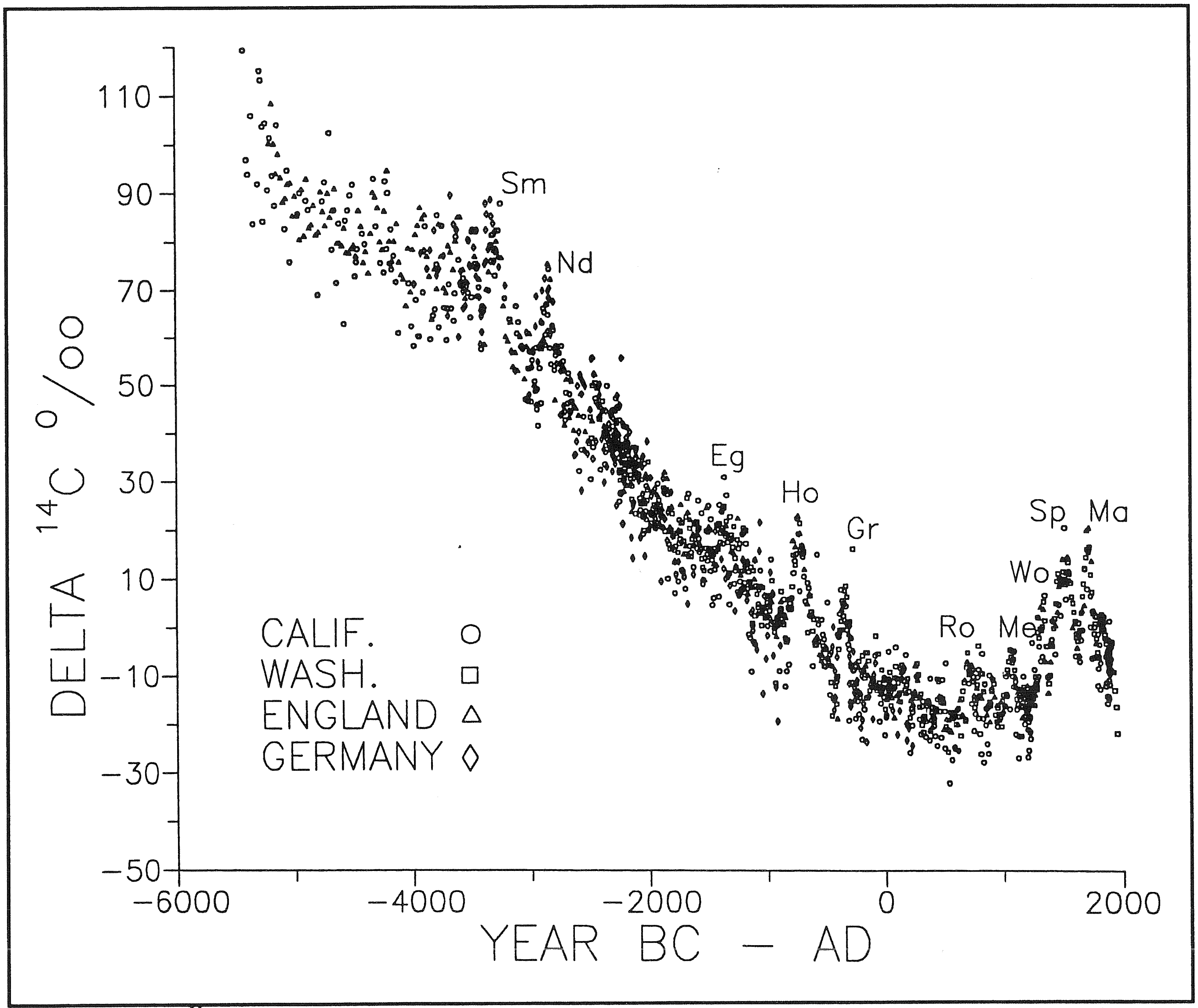

Figure 2.Names for Δ-^{14}C anomalies of the tree-ring-dated wood samples. Ma=Maunder, Sp=Sporer, Wo=Wolf, Me=Medieval, Ro=Roman, Gr=Green, Ko=Homeric, Eg=Egyptian, Nd=Noachan deluge, Sm=Sumarian. Symbol shapes as in Figure 1 but without Linick *et al* (1986) data. Raw determinations rather than smoothed or averaged values are shown to illustrate the coherence of these determinations, made in different global regions.

San Joaquin Marsh

Pollen analysis of a coastal California marsh provides confirmation of climatic change coincident with the radiocarbon production anomalies. San Joaquin Marsh (33°39'30"N, 117°51'30"W, elev. 2-3 m) is a small (82 ha) biotic preserve 7 km from the Pacific Ocean at Newport Bay, Orange County, California (Figure 3). The marsh is underlain by clay with occasional peat layers to ~8.5 m and with sand and clay layers to 12 m (Earth Research Associates 1977). Average annual precipitation at the marsh is 300 mm, with greatest rainfall in January. Mean monthly temperature ranges from 4°C in January to 29°C in September (Gustafson 1984).

Native upland vegetation surrounding the marsh is grassland, with dry bluffs covered by coastal sage scrub. Freshwater vegetation of the marsh is dominated by cattails (*Typha* spp.) and tule (*Scirpus californicus*), with willows (*Salix* sp.) common on dikes. Saline areas of the marsh and nearby Newport Bay are dominated by members of the Chenopodiaceae, and marsh rosemary (*Limonium californicum*) is common (Stevenson and Emery 1958).

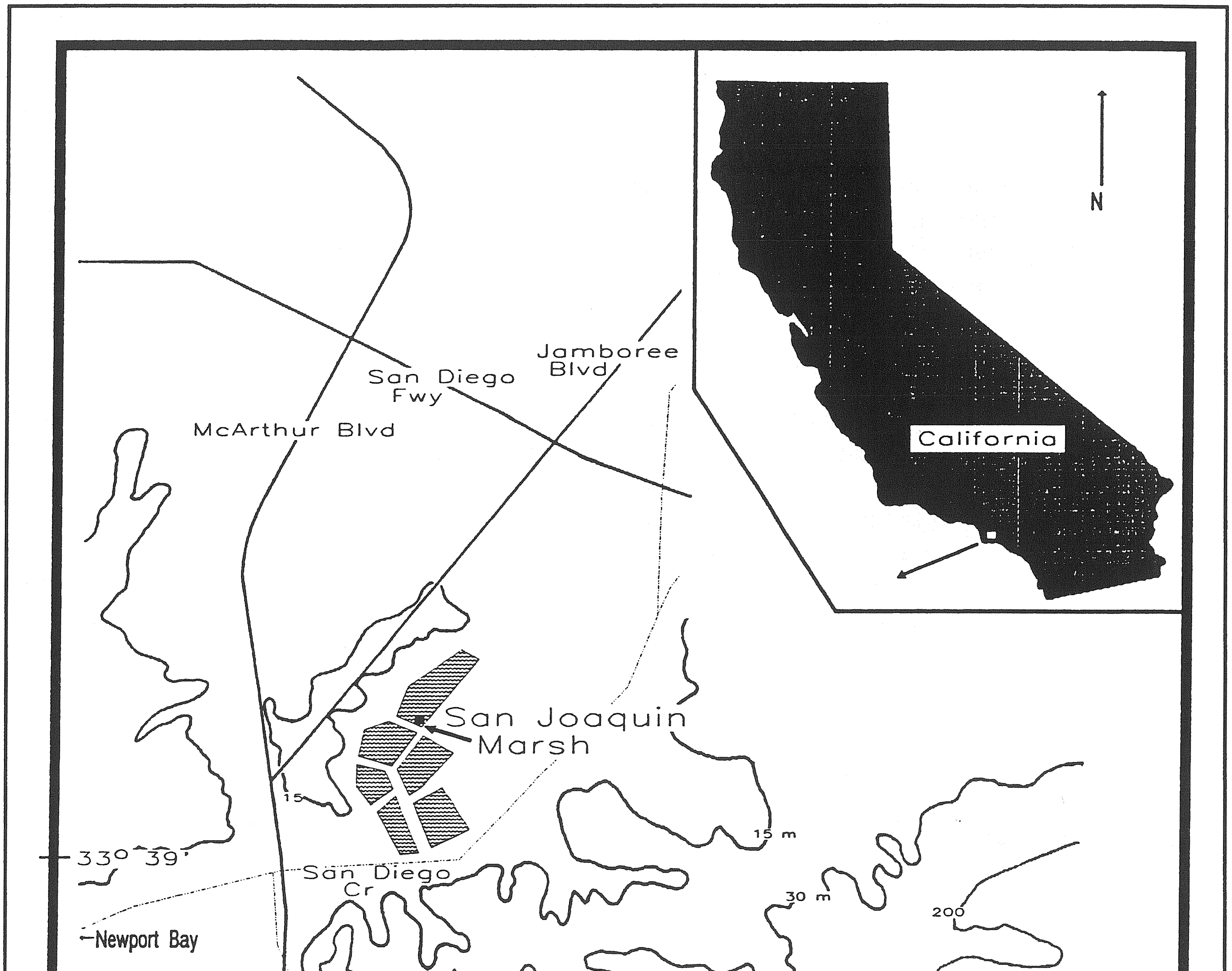

Figure 3.Map of San Joaquin Marsh area. Coring site indicated by black square; wavy pattern for water level controlled by dikes; dashed lines for San Diego and Bonita creeks; solid lines for 15-m contours and roads that influence drainage.

A 687-cm core was taken from San Joaquin Marsh in February 1989. The sediment is silty clay alternating with layers of black silty peat. Chronologic control is based on 5 radiocarbon dates, the first occurrence of the pollen of exotic taxa (AD 1776-1797), and the expansion of aquatic vegetation resulting from construction of the dikes (AD 1950).

Pollen extraction followed standard techniques for aquatic sediment (Faegri and Iversen 1975). Samples below 400 cm were filtered (Nytex(R) 3-10/3, 10-micron opening) because they contained much finely divided organic matter.

Dinoflagellates and the inner tests of foraminifera were recovered in certain samples. These are used as indicators of salt-water incursions without specific identification or additional processing of the sediment to recover calcareous foraminifera remains.

Prehistoric Change of Upland Vegetation

The percentage pollen diagram (Figure 4) is dominated by the "Other Compositae" and Chenopodiaceae-*Amaranthus* curves. Prior to ~3000 years BP, Compositae dominates (40-80%), but from ~3000 to 500 years BP it is supplanted by Chenopodiaceae-*Amaranthus* (40-70%). Chenopodiaceae-*Amaranthus* pollen is produced by xerophytic and halophytic plants in and around the marsh. West (1977) records Chenopodiaceae-*Amaranthus* up to 60% in halophytic vegetation in the Sacramento Delta

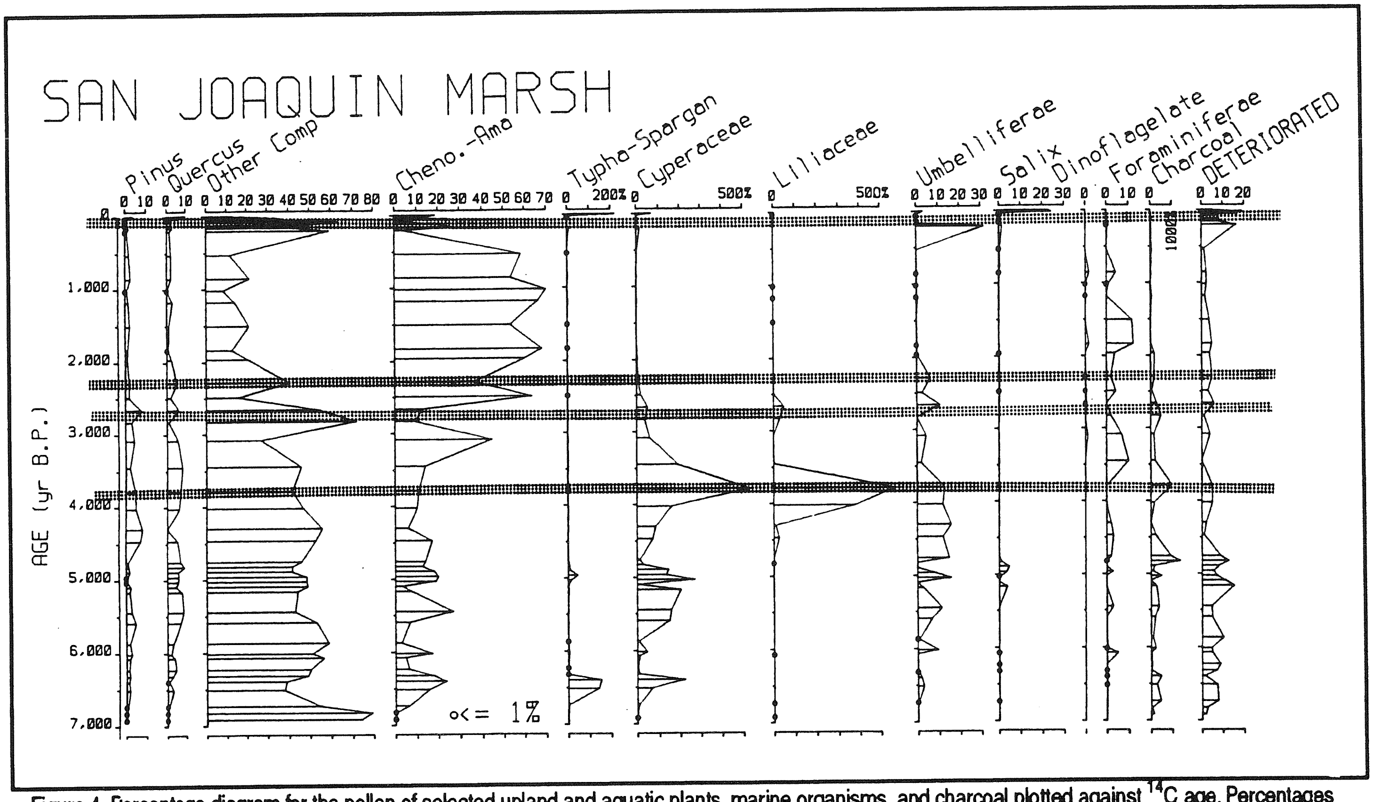

Figure 4. Percentage diagram for the pollen of selected upland and aquatic plants, marine organisms, and charcoal plotted against ^{14}C age. Percentages based on upland pollen sum. Shaded regions represent intervals of cold-wet climate corresponding to Little Ice Age (0-540 cal. BP), Greek (2450-2250 cal. BP), and Homeric (2830-2550 cal. BP) ^{14}C anomalies, and a cold-wet period (4470-3988 cal. BP) not matching a ^{14}C anomaly.

area. "Other Compositae" pollen is produced by many freshwater marsh plants (Gustafson 1984), but it also is abundant (10-40%) in California grassland (Adam 1967; Anderson and Davis 1988). Whether the source is grassland or marsh, a preponderance of Compositae pollen indicates vegetation more mesic than that characterized by Chenopodiaceae-*Amaranthus* dominance.

History of Marsh Vegetation

Prior to 4500 years BP, the pollen of sedges (*Cyperaceae*), lilies (*Liliaceae*), cattails (*Typha-Sparganium*), carrot family (*Umbelliferae*), and willows (*Salix*) documents the freshwater status of the marsh (Figure 4). Later, as sea level neared modern values, halophytic taxa dominated; Chenopodiaceae-*Amaranthus* pollen reaches 68%, and pollen of *Limonium*, a salt marsh plant, is present. Marine/estuarine organisms (dinoflagellates and foraminifera) co-occur with pollen of salt marsh plants, indicating salt water regularly reached the site.

After salt marsh became generally established, freshwater species invaded briefly while salt water was displaced by increased discharge in the watershed. These freshwater events are indicated by increased percentages in pollen of freshwater plants Cyperaceae, Liliaceae, and Umbelliferae (3800 and 2800 years BP), and by decreases of Chenopodiaceae-*Amaranthus*, dinoflagellates, foraminifera, and *Limonium* (2800, 2300, and after 560 years BP) (Figure 4). Abrupt increases of Typha-*Sparganium* and *Salix* show the effects of human management since 1950.

Discussion

The cool/wet periods at about 3800, 2800, 2300, and after 560 years BP, apparent in both the aquatic and upland vegetation (Figure 4), coincide with periods of global cooling, and (except the 3800-year-BP event) with ^{14}C production maximum. The post-560-year-BP period correlates with the Little Ice Age, the Matthes advances in the Sierra Nevada (Scuderi 1984, 1987), cooling in the White Mountains (LaMarche 1978), and reduced sea surface temperatures in the Santa Barbara Basin (Pisias 1978). The match is not exact because Scuderi (1984, 1987) lists four events in the last 500 years, but only two events (Compositae peaks at 140 and 360 years BP) are recorded at San Joaquin Marsh (Table 2).

The freshwater events at 2800 and 2300 years BP match Recess Peak advances (Scuderi 1984), but 1850 and 1100 years BP glacial advances are not recorded at San Joaquin Marsh. The 2800- and 2300-year BP events appear to be very rapid, large-scale climatic fluctuations. Many sites in western North America appear to record cold/wet climate at this time (Table 3). Conifer expansion at low elevation and increased lake levels were widespread in western North America during the Homeric

Minimum. The combined tree-ring calibrated age of this cold/wet climate is 2874-2759 cal BP, closely matching the age (2830-2550) of the ^{14}C anomaly.

Pisias (1978) estimates sea surface cooling in the Santa Barbara Basin by 3°C during the Greek Minimum, but samples dating to the Homeric

Table 2
Age of Neoglacial Climatic Events Recorded at San Joaquin Marsh and Elsewhere in California

San Joaquin Marsh ^{14}C BP, Interpolated (Dendro-corrected BP)	Sierra Nevada Glacial Events Scuderi 1984, 1987 Tree Ring Dates BP	Mono Lake High Stands Stine, 1990 (Dendro-corrected BP)	Delta ^{14}C Anomalies Stuiver & Kra, 1986 Tree Ring Dates BP
40 (290 - 0)	—	Historic High Stand (97 - 35)	Historic Minimum 70 - 40
137 (418 - 0)	Matthes Glaciation 134	—	Dalton Minimum 185 - 155
357 (540 - 0)	Matthes Glaciation 334	Clover Ranch High Stand (375 - 296)	Maunder Minimum 410 - 210
—	Matthes Glaciation 474	Danberg Beach High Stand (550 - 465)	Sporer Minimum 570 - 420
—	—	Rush Delta High Stand (680 - 605)	Wolf Minimum 745 - 620
—	—	Post Office High Stand (926 - 786)	Medieval Minimum 1020 - 880
—	—	—	Roman Minimum 1330 - 1130
2287 (2710 - 2049)	Recess Peak Glaciation 2200	—	Greek Minimum 2450 - 2250
2830 (3318 - 2749)	—	—	Homeric Minimum 2830 - 2550
3787 (4470 - 3988)	—	Dechambeau Ranch High Stand (4025 - 3608)	—

Table 3
Dates of the "Homeric Minimum" Cold/Wet Period in Western North America

Location	Age	Reference
Diamond Pond, OR	2700 ± 50 years BP	Mehringer and Wigand 1986
Rattlesnake Cave, ID	2790 ± 250 years BP	Davis *et al* 1986
Mission Cross Bog, NV	2470 ± 100 years BP	Thompson 1984
Sevier Lake, UT	2560 ± 65 years BP	Oviatt 1988
Montezuma Well, AZ	2885 ± 50 years BP	Shafer 1989
Lake Cahuilla, CA	2630 ± 120, 2600 ± 120 years BP	Waters 1989
Bonfire Shelter, TX	2780 ± 110 years BP	Bryant 1978
CALIBRATED AGE	2874-2759 cal BP - 925-810 cal BC	

Minimum could not be analyzed (a "gray layer" in the core). This cooling is comparable to Little Ice Age cooling in coastal southern California (3°C, Koerper *et al* 1985; 2°C, Pisias 1978).

The magnitude and brief duration of the Homeric, Greek, and Little Ice Age events makes them intriguing examples of rapid climatic change. Their correspondence to radiocarbon anomalies suggests a causal mechanism and permits precise dating of climate change, because the anomalies are dated by tree-rings (VanGeel and Mook 1989). The extent of the ^{14}C/climate association appears to be global. The cooling is recorded throughout western North America (Table 3) and in Europe (Nesje and Kvamme 1991; 2595±85, 2360±80 years BP), Asia (Grove 1988 p. 318; 2980±150, 2920±100 years BP), and the southern hemisphere (Hope and Petersen 1975; 2930±100, 2470±80 years BP).

Regardless of the causal mechanism(s) (solar, climatic, geomagnetic), the Δ-^{14}C curves provide a chronology for global, high-frequency climatic change. Milankovitch cycles have provided a reliable timing mechanism for climate change on long time scales during the Pleistocene (Hays *et al* 1976; Martinson *et al* 1987). The tree-ring chronology of radiocarbon anomalies can provide a similar function for the Holocene. Theoretical studies (Stuiver and Braziunas 1988; Hood and Jirikowic 1990) are needed to understand the causal mechanisms for the ^{14}C/climate association, and precise dating of climatic sequences is needed to confirm the global nature of the association and to identify any Holocene climatic fluctuations produced by other forcing functions.

Acknowledgments

We thank Dr. Philip de Barros, The Chambers Group, and The California Department of Transportation for supporting this project; Bill Bretz, Steward of San Joaquin Marsh, for permission to core the site; Bill Bretz, Henry Koerper, Kevin Moodie, and Jeanne De Lanoise for assistance in coring the marsh; and Henry Koerper, Andy Cohen, and Paul Damon for information and discussion used in preparation of this manuscript. Nicklas Pisias provided temperature data for Santa Barbara Basin, Malcolm Hughes and Lisa Graumlich provided LaMarche's tree-ring data. Supplementary pollen analyses and preparation of the manuscript were supported by NSF grants SES 8719273 and ATM-8619467

References

Adam, DP, 1967. Late Pleistocene and Recent palynology in the central Sierra Nevada, California. In EJ Cushing and HE Wright, Jr., Eds., *Quaternary Paleoecology*, Yale Univ. Press, New Haven, Conn., pp. 275-301.

Anderson, RS, and OK Davis, 1988, Contemporary pollen rain across the central Sierra Nevada, California: The relationship to modern vegetation types. *Arctic and Alpine Res.* 20:448-460.

Anderson, RY, 1991. A Solar/Geomagnetic-^{14}C-climate connection: evidence from mid-Holocene varves in a Minnesota lake. *8th PACLIM Workshop*. Tech. Report 26, Interagency Ecolog. Stud. Progr. Sacramento-San Joaquin Estuary.

Barnola, JM, D Raynaud, TS Korotkevich, and C Loris, 1987. Vostok ice core provides 16,000-year record of atmospheric CO^2. *Nature*. 329:408-413.

Benoist, JP, F Glangeaud, N Martin, JL Lacoume, C Lorius, and A Oulahman, 1982. Study of climatic series by time-frequency analysis. Pgs. 1902-1905 in *Proceedings ICASSP82*. IEEE Press:New York.

Beer, J, U Siegenthaler, G Bonani, RC Finkel, H Oescheger, M Suter, and W Wolfli, 1988. Information on past solar activity and geomagnetism from ^{10}Be in the Camp Century ice core. *Nature*. 331:675-679.

Brooks, CEP, 1949. *Climate Through The Ages*. 1st Ed. Pillans and Wilson:Edinburgh. 439 pp.

Bryant, VM Jr, 1978. Late Quaternary pollen records from the east-central periphery of the Chihuahuan Desert. In RH Wauer and DH Riskind (Eds.) *Symposium on Biological resources of the Chihuahuan Desert Region, United States and Mexico*. USDI Transactions and Proceedings. 3:3-21

Damon, PE, 1968. Radiocarbon and climate (A comment on a paper by H Suess). *Meteorological Monographs*. 8:151-154.

Damon, PE, JC Lerman, and A Long, 1978. Temporal fluctuations of atmospheric 14C: causal factors and implications. *Ann. Rev. Earth Plant. Sci.* 6:457-494.

Damon, PE, and TW Linick, 1986. Geomagnetic-Heliomagnetic modulation of atmospheric radiocarbon production. *Radiocarbon*. 28:266-278.

Dansgaard, W, SJ Johnsen, HB Clausen, and CC Langway Jr, 1971. Climatic record revealed by the Camp Century ice core. Pgs. 37-56 in KK Turekian (ed.) *The Late Cenozoic Glacial Ages*. Yale Univ Press:New Haven.

Dansgaard, W, SJ Johnsen, HB Clausen, D Dahl-Jensen, N Gundestrup, CH Hammer, and H Oescheger, 1984. North Atlantic oscillations revealed by deep Greenland ice cores. *Geophysical Monographs*. 29:288-298.

Davis, OK, JC Sheppard, and S Robertson, 1986. Contrasting climatic histories for the Snake River Plain result from multiple thermal maxima. *Quaternary Research*. 26:321-339.

DeDeckker, P, T Correge, and J Head, 1991. Late Pleistocene record of cyclic eolian activity from tropical Australia suggesting the Younger Dryas is not an unusual climatic event. *Geology*. 19:602-605.

deVries, HL, 1958. Variation in concentration of radiocarbon with time and location on Earth. *Koninkl Nederlandse Akad Wetenschappen, Proc. Ser.B.* 61:94-102.

Earth Research Associates, 1977. *Preliminary soils engineering investigation on the preservation of San Joaquin Freshwater Marsh Project*. Report to the University of California, Irvine, Office of Physical Planning and Construction.

Eddy, JA, 1977. Climate and the changing sun. *Climate Change*. 1:173-190.

______, 1976. The Maunder Minimum. *Science* 192:1189-1202.

Faegri, K, and J Iversen, 1975. *Textbook of pollen analysis*. Hafner Press, NY. 295 pp.

Genthon, C, *et al*, 1987. Vostok ice core: climatic response to CO^2 and orbital forcing changes over the last climatic cycle. *Nature*. 329:414-418.

Gleissberg, W, 1958. The 80-year sunspot cycle. *British Astron. Assoc. Jour.* 68:148-157.

Grove, JM, 1988. *The Little Ice Age.* Methuen, London.

Gustafson, S, 1984. *San Joaquin freshwater marsh reserve.* University of California Natural Reserve System Brochure.

Halfman, JD, and TC Johnson, 1988. High-resolution record of cyclic climatic change during the past 4 ka from Lake Turkana, Kenya. *Geology.* 16:496-500.

Hays JD, J Imbrie, and NJ Shackleton, 1976. Variations in the Earth's orbit: pacemaker of the Ice Ages. *Science.* 194:1121-1132.

Hood, LL, and JL Jirikowic, 1989. Recurring variations of probable solar origin. *Geophysical Research Letters* 17:85-88.

Hope, GS, and JA Peterson, 1975. Glaciation and vegetation in the high New Guinea Mountains. In RP Suggate and MM Cresswell, Eds., *Quaternary Studies*, Royal Society New Zealand, pp. 155-162.

Houtermans, JC, 1971. *Geophysical interpretations of bristlecone pine radiocarbon measurements using a method of Fourier analysis for unequally spaced data.* PhD dissertation. University of Bern:Switzerland.

Iversen, J, 1973. The development of Denmark's nature since the last glacial. *Danmarks Geologiske Undersogelse.* 5(7C).

Keeling, CD, SC Piper, and M Heimann, 1989. A three-dimensional model of atmospheric CO_2 transport based on observed winds. 4. Mean annual gradients and interannual variations. *AGU Geoph. Mon.* 55.

Kromer, B, M Rhein, M Bruns, H Schoch-Fischer, KO Munnich, M Stuiver, and B Becker, 1986. Radiocarbon calibration data for the 6th to 8th millennia BC. *Radiocarbon.* 28(2B):954-960.

LaMarche, VC Jr, 1978. Tree-ring evidence of past climatic variability. *Nature.* 276:334-338.

Lamb, HH, 1977. *Climate history and the future.* Princeton University Press.

Landscheidt, T, 1987, Long-Range forecasts of solar cycles and climate change. Pgs. 421-445 in MR Rampino, JE Sanders, WS Newman, and LK Konigsson (eds.) *Climate History, Periodicity, and Predictability.* Van Nostrand Reinhold:New York.

Lean, J, 1991. An esitmate of the sun's photon output during the Maunder Minimum. *Abstract SH41A-3 Spring AGU Meeting.* p.224.

Libby, WF, 1955. *Radiocarbon dating.* Univ. Chicago Press.

Linick, TW, A Long, PE Damon, and CW Ferguson, 1986. High-precision radiocarabon dating of bristlecone pine from 6554 to 5350 BC. *Radiocarbon.* 28(2B):943-953.

Linick, TW, HE Suess, and B Becker, 1985. La Jolla measurements of radiocarbon in south German oak tree-ring chronologies. *Radiocarbon.* 27:20-32.

Martinson, DG, NG Pisias, JD Hays, J Imbrie, TC Moore Jr, and MG Shackleton, 1987. Age dating and orbital theory of the ice ages: development of a high-resolution 0-300,000-year chronostratigraphy. *Quaternary Research.* 27:1-29.

Mehringer, PJ Jr, and PE Wigand, 1986. Western Juniper in the Holocene, In RL Everett (ed.) *Westwide Pinyon-Juniper Conference.* U.S. Forest Service Gen. Tech. Report INT-215.

Neftel, A, H Oeschger, J Schwander, B Stauffer, and R Zumbrunn, 1982. Ice core sample measurements give atmospheric CO_2 content during the past 40,000 years. *Nature.* 295:220-223.

Nesje, A, and M Kvamme, 1991. Holocene glacier and climate variations in western Norway: Evidence for early Holocene glacier demise and multiple Neoglacial events. *Geology.* 19:610-612.

Oviatt, CG, 1988. Late Pleistocene and Holocene lake fluctuations in the Sevier Lake Basin, Utah, USA. *Journal Paleolimnology.* 1:9-21.

Pearson, GW, JR Pilcher, MGL Baillie, DM Corbett, and F Qua, 1986. High-precision ^{14}C measurement of Irish oaks to show the natural ^{14}C variations from AD 1840-5210 BC. *Radiocarbon.* 28(2B):911-934.

Pearson, GW, and M Stuiver, 1986. High-precision calibration of the radiocarbon time scale, 500-2500 BC. *Radiocarbon.* 28(2B):839-862.

Pestiaux, P, JC Duplessy, and A Berger, 1987. Paleoclimatic variability at frequencies ranging from 10^{-4} cycle per year to 10^{-3} cycle per year — Evidence for nonlinear behavior of the climate system. Pgs. 285-299 in MR Rampino, JE Sanders, WS Newman, and LK Konigsson (eds.) *Climate History, Periodicity, and Predictability.* Van Nostrand Reinhold:New York.

Pisias, NG, 1983. Geologic time series from deep-sea sediments: Time scales and distortion by bioturbation. *Marine Geology.* 51:99-113.

______, 1978. Paleoceanography of the Santa Barbara Basin during the last 8000 years. *Quaternary Research.* 10:366-385.

Pisias, NG, JP Dauphin, and C Sancetta, 1973. Spectral analysis of late Pleistocene-Holocene sediments. *Quaternary Research.* 3:3-9.

Pittock, AB, and Shapiro, 1982. Assessment of evidence of the effect of solar variations on weather and climate. In *Solar Variability, Weather, and Climate*: National Academy Press.

Povince, P, 1983. Short-term variations in radiocarbon concentration with the 11-year solar cycle. *Radiocarbon.* 25:259-266.

Schmidt, B, and W Gruhle, 1988. Klima, Radiokohlenstoffgehalt und Dendrochronologie. *Naturwissenschafliche Rundschau.* 41(5):177-182. (Translation by T Jull).

Schnitker, D, 1982. Climatic variability and deep ocean circulation, Evidence for the North Atlantic. *Palaeo. Palaeo. Palaeo.* 40:213-234.

Schove, DJ, 1980. The 200-, 22-, and 11-year cycles and long series of climatic data, mainly since A.D. 200. Pgs. 807-100 in *Sun and Climate.* Centre National d'Etudes Spatales.

______, 1955. The sunspot cycle, 649 B.C. to A.D. 2000. *Jour. Geophys. Research.* 60:127-146.

Scuderi, LA, 1987. Glacier variations in the Sierra Nevada, California, as related to a 1200-year tree-ring chronology. *Quaternary Research.* 27:220-231.

______, 1984. *A dendroclimatic and geomorphic investigation of late-Holocene glaciation, southern Sierra Nevada, California.* PhD dissertation. Univ. California:Los Angeles, 247 pp.

Shafer, DS, 1989. *The timing of late Quaternary monsoon precipitation maxima in the southwest United States.* PhD dissertation. University of Arizona:Tucson. 234 pp.

Shuti, H, and Y Yujiang, 1990. Paleoclimatic variation of the Balikun Lake Region of Xinjiang during the past 35,000 years. *Acta Geographica Sinica.* 45:350-362. (Translation by D Kumai).

Sonett, CP, 1990. Atmospheric 14C variations: a Bayesian prospect. Pgs. 143-159 in PF Fougere (ed.) *Maximum Entropy and Bayesian Methods.* Kluwer Academic Publ.:Netherlands.

Starkel, L, 1987. Long-term and short-term rhythmicity in terrestrial landforms and deposits. In MR Rampino, JE Sanders, WS Newman, and LK Konigsson, Eds., *Climate: History, Periodicity, and Predictability*, Van Nostrand Reinhold Company, NY. pp. 323-332.

Stevenson, RE, and KO Emery, 1958. *Marshlands at Newport Bay, California.* University Southern Calif. Occasional Paper 20.

Stine, S, 1990. Late Holocene fluctuations of Mono Lake, eastern Calfiornia. *Palaeo. Palaeo. Palaeo.* 78:333-381.

Stuiver, M, 1965. Carbon-14 content of 18th and 19th Century Wood: Variations Correlated with Sunspot Activity. *Science.* 149:533-537.

Stuiver M, and B Becker, 1986. High-precision decadal calibration of the radiocarbon time scale AD 1950-2500 BC. *Radiocarbon.* 28(2B):863-910.

Stuiver, M, and TF Braziunas, 1988. The solar component of the atmospheric ^{14}C record, Pgs. 245-266 in FR Stephenson and AW Wolfendale (eds.) *Secular Solar and Geomagnetic Variations in the Last 10,000 Years.* Kluwer Academic Publishers:Dorchredt.

Stuiver, M, TF Braziunas, B Becker, and B Kromer, 1991. Climatic, solar, oceanic, and geomagnetic influences on late-Glacial and Holocene atmospheric 14C/12C change. *Quaternary Research* 35:1-24.

Stuiver, M, and RS Kra, 1986. Proceedings of the twelfth international radiocarbon conference - Trondheim, Norway. *Radiocarbon.* 28(2B).

Stuiver M, B Kromer, B Becker, and CW Ferguson, 1986. Radiocarbon age calibration back to 13,300 years BP and the ^{14}C age matching of the German oak and US bristlecone pine chronologies. *Radiocarbon.* 28(2B):969-979.

Stuiver, M, and GW Pearson, 1986. High-precision calibration of the radiocarbon time scale, AD 1950-500 B.C. *Radiocarbon.* 28(2B):805-838.

Suess, HE, 1978. La Jolla measurements of radiocarbon in tree-ring dated wood. *Radiocarbon.* 20:1-18.

______, 1965. Secular variations of the cosmic-ray-produced carbon 14 in the atmosphere and their interpretations. *J. Geophys. Res.* 70:5937-5952.

Thomson, DJ, 1990. Time series analysis of Holocene climate data. *Phil. Trans. Roy. Soc. Lond. Ser.A.* 330:601-616.

Thompson, RS, 1984. *Late Pleistocene and Holocene environments in the Great Basin.* PhD dissertation. University Arizona, Tucson, 209 pp.

Van Geel, B, and WG Mook, 1989. High-resolution 14C dating of organic deposits using natural atmospheric 14C variations. *Radiocarbon* 31:151-155.

Waters, MR, 1989. Late Quaternary lacustrine history and paleoclimatic significance of pluvial Lake Cochise, southeastern Arizona. *Quaternary Research* 32:1-12.

West, GJ, 1977. *Late Holocene vegetation history of the Sacramento-San Joaquin Delta, California.* Report to Calif. Department of Parks and Recreation, Interagency Agreement B-50173.