A Solar-Luminosity Model and Climate

Charles A. Perry

U.S. Geological Survey, Lawrence, Kansas 66049

ABSTRACT

Although the mechanisms of climatic change are not completely understood, the potential causes include changes in the Sun's luminosity. Solar activity in the form of sunspots, flares, proton events, and radiation fluctuations has displayed periodic tendencies. Two types of proxy climatic data that can be related to periodic solar activity are varved geologic formations and freshwater diatom deposits. A model for solar luminosity was developed by using the geometric progression of harmonic cycles that is evident in solar and geophysical data. The model assumes that variation in global energy input is a result of many periods of individual solar-luminosity variations. The 0.1-percent variation of the solar constant measured during the last sunspot cycle provided the basis for determining the amplitude of each luminosity cycle. Model output is a summation of the amplitudes of each cycle of a geometric progression of harmonic sine waves that are referenced to the 11-year average solar cycle.

When the last eight cycles in Emiliani's oxygen-18 variations from deep-sea cores were standardized to the average length of glaciations during the Pleistocene (88,000 years), correlation coefficients with the model output ranged from 0.48 to 0.76. In order to calibrate the model to real time, model output was graphically compared to indirect records of glacial advances and retreats during the last 24,000 years and with sea-level rises during the Holocene. Carbon-14 production during the last millenium and elevations of the Great Salt Lake for the last 140 years demonstrate significant correlations with modeled luminosity. Major solar flares during the last 90 years match well with the time-calibrated model.

INTRODUCTION

The climate of the Earth has had major variations throughout its geological record and minor fluctuations during its historical record. Although causes of major climatic variations, especially the ice-age cycle, are not completely understood, some of the more important causal mechanisms include continental drift, changes in the Earth's relative position with the Sun, volcanic activity, changes in atmospheric gases, and variations in solar output. The most widely accepted theory for the cause of the ice-age cycles of the Pleistocene is the Milankovitch orbital cycles coupled with positive feedback from the greenhouse effect[1]. Evidence in support of the Milankovitch theory is substantial[2,3], but there are still problems in its quantitative aspects. Recent work by Ramanathan et al.,[4] which involved satellite measurements of global radiation, indicates that clouds may cool the Earth more than they warm it, thus injecting a source of uncertainty into the models used to study the greenhouse effect.

The most direct mechanism for climate change would be a decrease or increase in the amount of radiant energy reaching the Earth. Because the Milankovitch orbital theory can account for only a maximum of 0.1-percent change in the total global energy and must rely on a complex redistribution of that energy to force a climatic change, one can look to the Sun as a possible source of larger energy fluctuations. Earth-satellite measurements of the so called "solar constant" in the last decade have revealed that it is far from being a constant. Total energy reaching the Earth decreased between 1980 and 1986 by more than 0.1 percent[5]. If this rate of decrease were to continue, the world would be entering another global ice age within centuries. However, the solar constant has increased since 1987 along with increased solar magnetic activity. Evidence of solar-forced climatic variations on the order of years to centuries is accumulating. This paper presents a simple model for solar luminosity that shows significant correlations with both short- and long-term climatic variations.

SOLAR ACTIVITY

Solar activity is quite variable and has displayed periodic tendencies. An obvious indicator of solar activity are sunspots. They have been counted in various ways for nearly 300 years, and several periodicities are evident. The best-known feature of the sunspot record is that the number observed follows an approximate 11-year cycle. G.E. Hale[6] discovered that the polarity of the sunspots goes through an approximate 22-year cycle. Later, W. Gleissberg[7] noted that the maximum number of sunspots for each 11-year cycle goes through an approximate 88-year cycle. This group could include a weak cycle of 44 years if the two sunspot maximums within a polarity cycle (22 years) are averaged. When the periods of 5.75 years found by Cole[8] and 179 years found by Cohen and Lintz[9] are added, an apparent progression of cycles in sunspot data of 5.75, 11, 22, 44, 88, and 179 years appears.

Since the advent of artificial Earth satellites and improvements in ground-based observing instruments, other features of the Sun were discovered to be periodic in nature. Table 1 is a list of some of the observed periodicities of several features of the Sun. A complete list of all periodicities found by each investigator is provided by Perry[10].

Table 1. *Observed periods of solar activity*

Investigator (First)	Year	Type of geological data	Reported period (RP)(Years)	Integer N where $RP \approx (11)2^N$
Haubold, H.J.[11]	1987	Neutrinos	0.64	-4
Ichimoto, K.[12]	1985	Flares	1.41	-3
LaClare, F.[13]	1983	Diameter	2.74	-2
Lomb, N.R.[14]	1980	Sunspots	5.49	-1
Haubold, H.J.[11]	1987	Neutrinos	5.26	-1
Lomb, N.R.[14]	1980	Sunspots	11.0	0
Gough, D.O.[15]	1988	Neutrinos	11.0	0
Willson, R.C.[5]	1988	Total flux	11.0	0
Gilliland, R.L.[16]	1981	Diameter	11.0	0
Wilson, P.R.[17]	1988	Ephemeral active region	22	1
Hale, G.E.[6]	1924	Sunspot polarity	22	1
Lomb, N.R.[11]	1980	Sunspots	47	2
Cole, T.W.[8]	1973	Sunspots	88	3
Cohen, T.J.[9]	1974	Sunspots	179	4

SOLAR CYCLES AND LUMINOSITY VARIATIONS

The luminosity of the Sun has increased and decreased in phase with the 11-year solar cycle[5], and this variation has been measured at approximately 0.1 percent of the total flux from sunspot maximum to sunspot minimum. This variation in total energy is as large as that expected from the Milankovitch eccentricity cycle. The total flux from the Sun may have an even greater percentage variation over greater time scales. Proxy-climatic information can provide clues to these variations. Excellent records of sea temperature and sea level preserved in many geologic formations may provide possible indicators of solar luminosity.

Anderson[18, 19, 20, 21] has provided detailed analyses of several periodicities found in varve thicknesses. Varves are layered sediments that are assumed to be annual deposits in which the layer thickness is a function of climatic factors such as evaporation or precipitation. Another analysis of geologic data that supports and adds to the periodicities found by Anderson was performed by Pokras and Mix[22].

They found cycles in oxygen-18 composition of freshwater diatoms deposited on lake beds in tropical Africa. Periodicities that Anderson found in varves and those Pokras and Mix found in freshwater diatoms are listed in table 2.

Table 2. *Periodicities in selected geological data*

Investigator (First)	Year	Type of geological data	Reported period (RP)(Years)	Integer N where $RP \approx (11)2^N$
Anderson, R.Y.[18]	1961	Varves	22.1	1
Do.	do.	do.	40.2	2
Anderson, R.Y.[19]	1963	Varves	90	3
Anderson, R.Y.[20]	1989	Varves	180	4
Anderson, R.Y.[21]	1982	Varves	2,700	8
Pokras, E.M.[22]	1987	Diatoms	5,500	9
Do.	do.	do.	11,500	10
Do.	do.	do.	23,000	11
Anderson, R.Y.[20]	1982	Varves	20,000	11
Do.	do.	do.	100,000	13

The combination of reported periodicities in tables 1 and 2 reveals an interesting geometric progression. Each reported cycle (RP) can be approximated by the equation:

$$RP \approx 11 (2)^N, \tag{1}$$

where N is any integer, positive, negative, or zero. Using the three data sets (solar activity, varves, and diatoms), the geometric progression for the integer values of -4 to +13 lacks examples for N equal to 5, 6, 7, and 12. By including carbon-14 data periodicities of 740 (N approximately equal to 6) and 1,486 years[23] (N approximately equal to 7) and freshwater diatoms from a Mesozoic deposit with a periodicity of 43,000 years[24] (N approximately equal to 12), the mathematical progression has supporting physical evidence for 17 of the 18 integers from -4 through +13. There is evidence that the harmonic progression continues for values of N less than -4 and greater than 13 in other geophysical data sets that are indicative of climate[10]. Certain reported cycles do not fit the progression ideally, but they do have a systematic variation, quite like the distribution of sunspot cycle lengths since 1700 AD[10]. The variation in the lengths of solar-activity cycles may be a function of seismonuclear processes within the Sun's core.[25]

The geometric progression described by equation 1 can be considered a "fundamental" harmonic progression, with each cycle length being an integer doubling or halving the previous cycle. This is different from "simple" harmonics, which are integer multiples of one-cycle length, such as the progression of 11, 22, 33, 44, 55, 66, and 77 years. The equation for this "simple" harmonic progression is 11 x N, with N equal to 1, 2, 3, 4, 5, 6, and 7. This important differentiation between fundamental and simple harmonics must be maintained throughout this discussion. Any designation of "harmonic progression" in this paper will imply an integer doubling or halving.
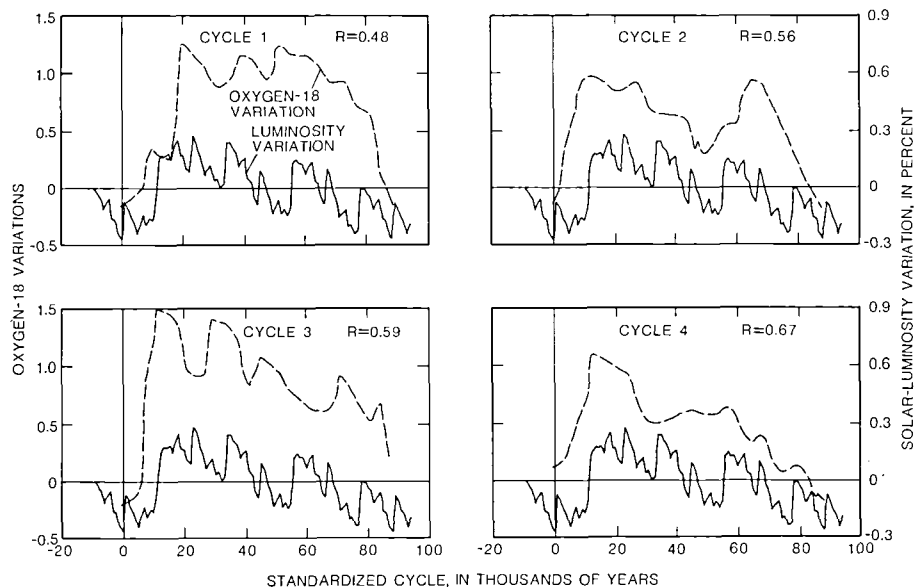
SOLAR-LUMINOSITY MODEL

The total instantaneous energy output of the Sun is hypothesized to be a summation of many individual harmonics. These variations would follow a simple sine-wave function with the amplitude in terms of a plus or minus percentage change. The solar-luminosity variation of 0.1 percent for the 11-year solar cycle provides the basis for the development of a harmonic progression of sine waves used in the summation. The strengths of spectral analyses of the solar and geophysical cycles suggest that the progression of amplitudes for each harmonic sine wave may not increase steadily with each progressively larger harmonic, but instead increases in a stepped manner. For instance, the 22-year cycle is evident in a variety of data, whereas the 44-year cycle has not been detected as often. The 88-year cycle is stronger in most data than the 176-year cycle. Of the longer period cycles, greater

spectral powers were found near 22,000 and 88,000 years than near 11,000 and 44,000 years. It appears that the amplitude of the odd-numbered harmonics (odd-numbered N, for example N = 1 for RP = 22) may be almost as large as the next even-numbered harmonic.The model algorithm was formulated to allow the odd-numbered harmonic cycles to have the same increase in amplitude as the even-numbered harmonic cycles following them. Model output is simply a summation of a series of harmonic sine waves.

CORRELATIONS OF MODEL WITH PROXY CLIMATIC DATA

Fourteen harmonic sine waves from 11 to 90,112 years were superimposed to generate a sequence of solar-luminosity variations. This sequence was compared cycle by cycle with a composite sequence of oxygen-18 variations in deep-sea cores from approximately 730,000 years ago to the end of the last glacial period[26]. Although more detailed oxygen-18 data are available from other sources, Emiliani's data were chosen for this analysis because they constituted a continuous record and had not been "orbitally tuned." There were eight complete glacial cycles during this time, with an average length of approximately 88,000 years. The first cycle (cycle #1) used in this analysis began 720,000 years ago, and the last one (cycle #8) ended about 22,000 years ago with the coldest period of the Wisconsin glaciation. Data from each of the eight cycles were standardized to a cycle length of 88,000 years. Oxygen-18 variations were not changed.

Graphical comparisons between the model and each of the eight cycles are shown in Fig. 1. The numerical correlations between luminosity variations of the model and the standardized oxygen-18 variations were 0.48 for cycle 1, 0.56 for cycle 2, 0.59 for cycle 3, and improving to 0.67 for cycle 4. Correlation coefficients for cycles 5, 6, 7, and 8 were 0.71, 0.76, 0.62, and 0.73, respectively. The average of the correlation coefficients for the eight cycles was 0.64, and for the last five cycles, 0.70. The probability of such good correlations occurring in unrelated data is quite small. A strong connection between cyclic solar activity, as expressed by the superimposed solar-luminosity cycles, and responses of the Earth's climate would be needed to produce such relations.


Figure 1. *Comparison of standardized cycles of oxygen-18 and solar-luminosity variations for glacial cycles 1-4.*
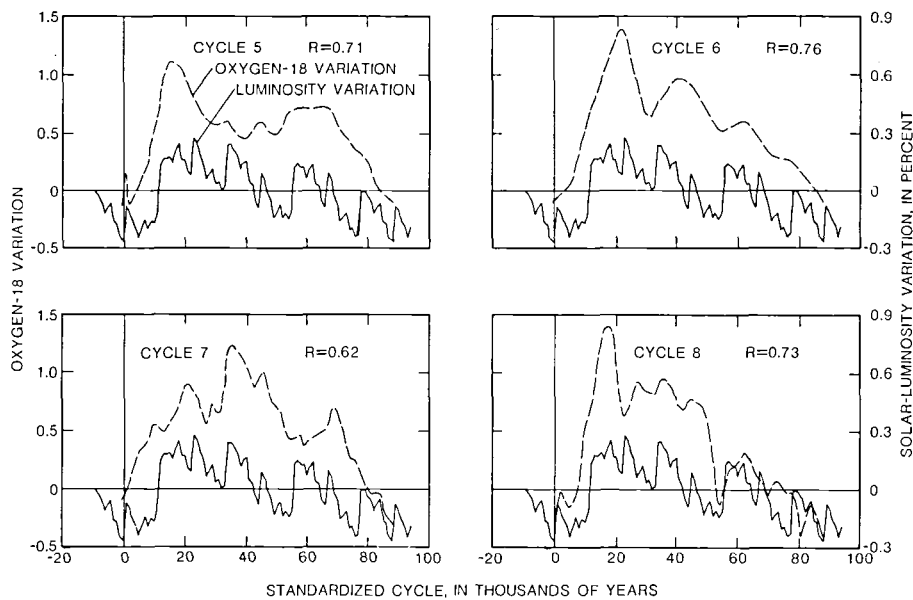
Figure 1 (continued). *Comparisons of standardized cycles of oxygen-18 and solar-luminosity variations for glacial cycles 5-8.*

## CALIBRATION OF MODEL TO REAL TIME

The model also was evaluated with the timing of recent well-dated climatic events. The solar-luminosity model was calibrated to a significant climatic event, and a graphical comparison of the timing of events before and after that match point was made. The most obvious match point occurs when all cycles are coming in phase together to produce a large increase of solar luminosity in a short time. Climatically, this time corresponds well with the very rapid melting of the last continental glacier approximately 10,000 years ago, the Pleistocene-Holocene boundary. This boundary became time 0, and luminosity variations were generated for a period of 14,000 years before to 12,000 years after this match point. This 26,000-year sequence of luminosity variations is plotted at 176-year intervals in Fig. 2.
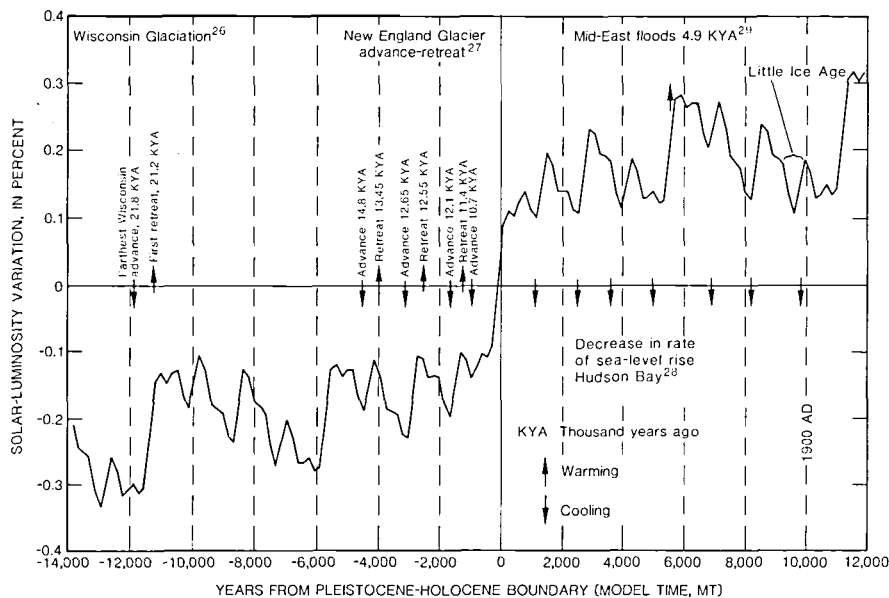
Figure 2. *Comparison of solar-luminosity model and climatic events during the last 24,000 years.*

185

The model output corresponds well with several significant climatic events during the last 24,000 years. The farthest Wisconsinan glacial advance is dated at 21.8 thousand years ago (KYA) followed by the first retreat at 21.2 KYA[27]. Later, readvances and retreats of the glacier in the New England area[28], match well with variations in the modeled luminosity. During the Holocene, decreases in the rate of sea-level rise measured on Hudson Bay shorelines[29] occurred at corresponding small values of luminosity. The "Little Ice Age" corresponded with the smallest luminosity value in the last 10,000 years. A major rise in sea level, chronicled by many Mid-Eastern civilizations[30], and measured along the French Coast by Ters[31] may be evidence of rapid melting of mountain glaciers and the remaining ice caps by a large increase in luminosity.

A comparison of the solar-luminosity model with more recent information was made with carbon-14 production in the atmosphere. Carbon-14 is produced by cosmic rays that are modulated by the solar wind. During times of increased solar output (high solar activity), the solar wind is strong, deflecting the cosmic rays away from the Earth[32]. Because the cosmic-ray flux is decreased, the production of carbon-14 decreases. During periods of low solar activity, more carbon-14 is produced. The bottom graph in Fig. 3 shows the relative rate of carbon-14 production during the last millennium as measured in tree rings (data from Damon[33]). The graph is inverted for direct comparison with the solar-luminosity model (lower solar output versus greater carbon-14 production) and plotted every 11 years. Evidence can be seen for the Wolf Minimum about 1300 AD, the Sporer Minimum about 1500 AD, and the Maunder Minimum, which ended with the return of increased solar activity, about 1700 AD. These three minima in solar activity correspond to the Little Ice Age. The solar-luminosity model from 9,000 to 9,950 Model Time [MT] follows the carbon-14 pattern closely. The correlation coefficient for these data is R = 0.82.
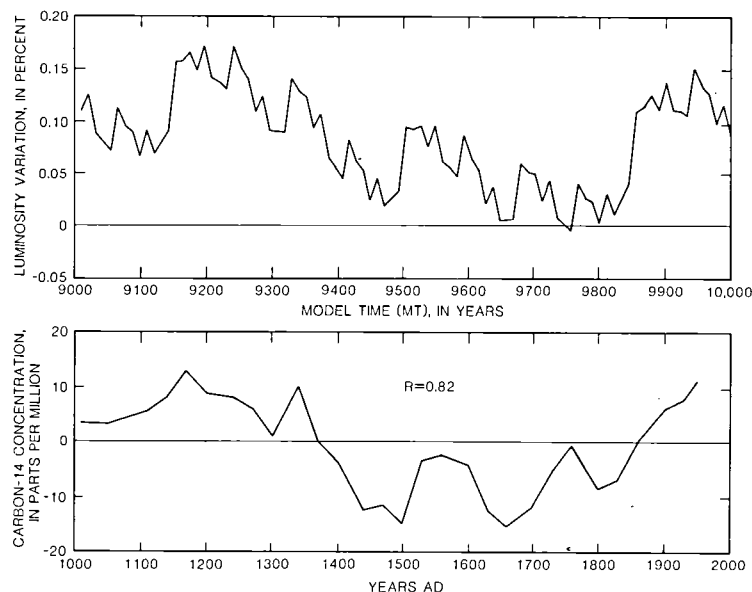
Figure 3. *Correlation of solar-luminosity model and carbon-14 concentrations in tree rings.*

The model was related also to recent climatic fluctuations. Elevations of the Great Salt Lake in Utah, which represent climatic conditions for a large geographical region, are compared with a detailed plot (yearly) of the modeled values (Fig. 4). Correlation of the model output and lake levels resulted in a correlation coefficient of 0.30. The correlation of model output with these data has an exciting side note. Major solar flares during the 90 years[34] match with large increases in modeled luminosity.
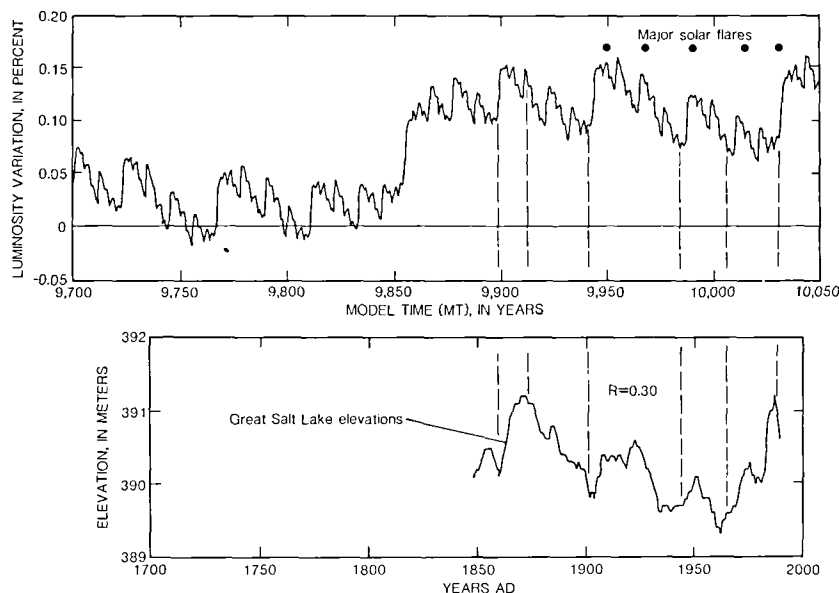
Figure 4. *Correlation of solar-luminosity model with elevations of the Great Salt Lake and occurrences of major solar flares.*

CONCLUSIONS

The total energy output of the Sun is hypothesized to be a summation of many periods of individual solar-luminosity variations. One such period is the 0.1-percent variation in solar luminosity that occurs during the 11-year sunspot cycle. Direct and indirect measurements of solar activity and luminosity demonstrate a harmonic progression of cyclicity that has been used to develop a simple model for solar output. Output from the model correlates well with proxy climatic records at different time scales. The model matches well with dated climatic fluctuations, which allowed the model to be calibrated to real time. Dates of advances and retreats of the Wisconsinan glaciation, dates of rates of change in sea-level rise, and sequence of sea levels during the Holocene provided climatic milestones that coincided directly with the solar-luminosity model. Time calibration of the model allows a glimpse at possible future solar-luminosity variations.

REFERENCES

1. Hays, J.D., J. Imbrie, and N.J. Shackleton, "Variations in the Earth's orbit--Pacemaker of the Ice Ages," Science, 194, 1121-1132, 1976.
2. Imbrie, J., and K.P. Imbrie, Ice Ages--Solving the Mystery, p. 224, Enslow Publ., New Jersey, 1979.
3. Berger, A., J. Imbrie, J.D. Hays, G. Kukla, and B. Saltzman, "Milankovitch and Climate," in Understanding the Response to Astronomical Forcing, p. 894, D. Reidel, The Netherlands, 1984.
4. Ramanathan, V., R.D. Cess, E.F. Harrison, P. Minnis, B.R. Barkstrom, E. Ahmad, and D. Hartmann, "Cloud-radiative forcing and climate--Results from the Earth radiation budget experiment," Science, 243, 57-63, 1989.
5. Willson, R.C., and H.S. Hudson, "Solar luminosity variations in solar cycle 21," Nature, 332, 810-812, 1988.
6. Hale, G.E., "Sunspots as magnets and the periodic reversal of their polarity," Nature, 113, 105, 1924.
7. Gleissberg, W., "The eighty-year cycle in auroral frequency numbers," British Astron. Assoc. J., 75, 227-231, 1965.
8. Cole, T.W., "Periodicities in solar activity", Solar Phys., 30, 103-110, 1973.
9. Cohen, T.J., and P.R. Lintz, "Long term periodicities in the sunspot cycle," Nature, 250, 398-399, 1974.

10. Perry, C.A., <u>A solar chronometer for climate--Astronomical and geophysical evidence</u>, p. 314, Ph.D. diss., University of Kansas, Lawrence, 1989.

11. Haubold, H.J., and E. Gerth, "Periodic behavior of solar activity and solar neutrino flux," Proc. 20th International Cosmic Ray Conference, Moscow, USSR, 4, 343-346, 1987.

12. Ichimoto, K., J. Kubota, M. Suzuki, I. Tohmura, and H. Kurokawa, "Periodic behavior of solar flare activity," Nature, 316, 422-424, 1985.

13. LaClare, F., "Solar diameter measurements," Austrian Astrophys., 125, 200-203, 1983.

14. Lomb, N.R., and A.P. Andersen," The analysis and forecasting of the Wolf sunspot numbers," Monthly Notes, Royal Astron. Soc., 190, 723-732, 1980.

15. Gough, D.O., "Deep roots of solar cycles," Nature, 336, 618-619, 1988.

16. Gilliland, R.L., "Solar radius variations over the past 265 years," Astrophys. J., 248, 1144-1155, 1981.

17. Wilson, P.R., R.C. Altrock, K.L. Harvey, S.F. Martin, and H.B. Snodgrass, "The extended solar activity cycles," Nature, 333, 748-750, 1988.

18. Anderson, R.Y., "Solar-terrestrial climatic patterns in varved sediments," New York Acad. Sci. Ann., 95, 424-439, 1961.

19. Anderson, R.Y., "Harmonic analysis of varve time series," J. Geophys, Res., 68, 877-893, 1963.

20. Anderson, R.Y., "A long geoclimatic record from the Permian," J. Geophys. Res., 87, 7285-7294, 1982.

21. Anderson, R.Y., "Solar forcing and pacing of climate change--A geologic perspective based on varves," written commun., 1-19, 1989.

22. Pokras, E.M., and A.C. Mix, "Earth's precession cycle and Quaternary climatic change in tropical Africa," Nature, 326, 486-487, 1987.

23. Sonett, C.P., "Very long solar periods and radiocarbon record," Rev. Geophys. and Space Phys., 22(3), 239-254, 1984.

24. Olsen, P.E., "A 40-million-year lake record of early Mesozoic orbital climatic forcing," Science, 234, 842-848, 1986.

25. Perry, C.A., "Speculation on a solar chronometer for climate," Proceedings of the Conference on the Climate Impact of Solar Variability, April 24-27, Goddard Space Flight Center, Greenbelt, Maryland, 1990.

26. Emiliani, C., "The cause of the Ice Ages," Earth Planetary Sci. Lett., 37, 349-352, 1978.

27. Larson, B.J., and B.D. Stone, <u>Late Wisconsin glaciation of New England</u>, p. 242, Kendall/Hunt, Dubuque, Iowa, 1982.

28. Schove, D.J., "Sunspot cycles and weather history," <i>in</i> <u>Climate</u>, M.R. Rampino, J.E. Sanders, W.S., Newman, and L.K. Konigsson, eds., p. 355-377, Van Nostrand Reinhold Co., New York, 1987.

29. Fairbridge, R.W., and C. Hillaire-Marcel, "An 8,000-yr palaeoclimatic record of the "Double-hale" 45-yr solar cycle," Nature, 268, 413-416, 1977.

30. Cornfield, G., <u>Archaeology of the Bible, Book by Book</u>, p. 8-9, Harper and Row Publ., New York, 1976.

31. Ters, M., "Variations in Holocene sea level on the French Atlantic Coast and their climatic significance," <i>in</i> <u>Climate</u>, M.R. Rampino, J.E. Sanders, W.S. Newman, and L.K. Konigsson, eds., p. 204-236, Van Nostrand Reinhold Co., New York, 1987.

32. Stuiver, M., "Statistics of the A.D. record of climate and carbon isotopic change," Radiocarbon, 25, 219-228, 1983.

33. Damon, P.E., "Solar induced variations of energetic particles at one A.U." <i>in</i> The Solar Output and Its Variations, O.R. White, ed., p. 429-448, Colorado Associated Press, Boulder, Colorado, 1977.

34. Dreschhoff, G.A.M., and E.J. Zeller, "Evidence of individual solar proton events in Antarctic snow," Solar Physics, (In Press), 1990.

C.A. Perry, U.S. Geological Survey, 4821 Quail Crest Place, Lawrence, KS 66049.