Variations in Radiocarbon Concentration and Sunspot Activity

M. STUIVER[1]

Geochronometric Laboratory, Yale University
New Haven, Connecticut

Abstract. Variations in cosmic-ray intensities will produce variations in C^{14} production in the atmosphere. A comparison is made between variations in sunspot activity and fluctuations in C^{14} concentration during the past 13 centuries. Although a definite conclusion is not reached, the evidence given suggests some correspondence between sunspot activities and C^{14} concentration in the atmosphere.

Variations in radiocarbon production. Recent observations of the general cosmic-ray level in the higher atmosphere have demonstrated large fluctuations in cosmic-ray activity that are correlated with the 11-year sunspot cycle. The correlation appears to be such that during sunspot maxima the cosmic-ray intensity in the higher atmosphere decreases. The integrated flux of primary cosmic-ray particles varies by a factor of 2 to 4 during one cycle [*Winckler*, 1960; *Simpson*, 1960]. The neutron production, which is responsible for the production of radiocarbon, also decreased by about the same factor during this period [*de Vries*, 1959]. A relation between the decrease in cosmic-ray flux and the number of sunspots during the maximum has not yet been demonstrated in detail, as the period covered by the observations is too short. Of the years with sunspot maxima (1947 and 1957) during which cosmic-ray depression has been observed, the reduction of cosmic rays is larger for 1957, the year with the highest sunspot activity. So it seems reasonable to assume that the depression of cosmic-ray intensity depends on the strength of the maximum: the larger the number of sunspots the greater the depression of cosmic-ray activity in the higher atmosphere. Even if one assumes a triggering mechanism rather than a strict proportionality, there must be a critical value for the number of sunspots required for the reduction of cosmic-ray activity.

Besides the variations in cosmic radiation discussed above, the C^{14} production by energetic protons produced by solar flares may be important. As was pointed out by *Simpson* [1960], the decrease in C^{14} production by cosmic rays during the sunspot maxima could partly be compensated by an increase of C^{14} production by protons coming from solar flares, especially during cycles with high sunspot activity. However, the calculations of the C^{14} production by protons contain some quantities with a large uncertainty, and furthermore the present C^{14} production in the atmosphere is in agreement with estimates derived from neutron densities. We shall assume, therefore, that the compensation of the depression of C^{14} production during the sunspot maximum is not very large.

Sunspot records are available during a period extending back more than 20 centuries, but the records after A.D. 1610 are the most reliable, having been made by telescope. The variations in sunspot activity can now be compared with variations in C^{14} activity. This is done for the last 1300 years in Figure 1. The curve giving the radiocarbon fluctuations in tree rings is that given by *Willis, Tauber, and Münnich* [1960]. Since these analyses were made at 50-year intervals, the sunspot curve has been derived from the curve of *Schove* [1955] by averaging the number of sunspots during the maxima over the same 50-year periods.

During the period from A.D. 800 to 1800 the sunspot curve shows 6 pronounced maxima at about A.D. 860, 960, 1110, 1360, 1560, and 1760. According to our hypothesis, we may expect a lower C^{14} production during periods with maximum sunspot activity. The curve for C^{14} concentration has therefore been inverted for readier comparison, so that a minimum in C^{14} activity corresponds to a maximum in the curve as

[1] Formerly at the C^{14} Laboratory, State University at Groningen, The Netherlands.

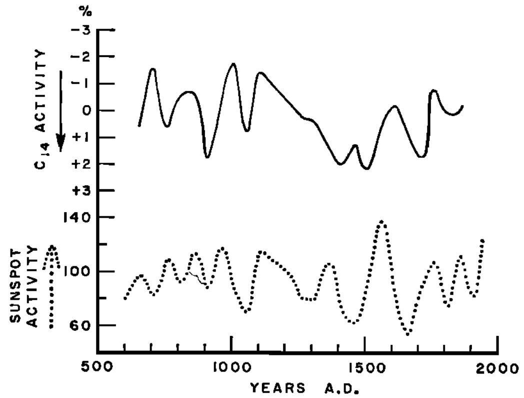

Fig. 1. Sunspot activity and radiocarbon activity variations during the past. The maxima in the C^{14} curve correspond to minima in C^{14} activity.

drawn. The inverted curve shows five pronounced 'maxima' during the period from A.D. 800 to 1800, differing on the average by only 35 years from the corresponding maxima in the sunspot curve. The only 'maximum' missing in the C^{14} curve is the one during the 14th century. During the earlier period from A.D. 650 to 800 no similarity between the curves is seen.

The curves given above suggest some correspondence between solar activity and radiocarbon activity in the atmosphere. However, considering the uncertainty of sunspot records before A.D. 1600, decisive evidence cannot be given. The period after A.D. 1600 is more suitable for this purpose and will be considered in more detail in the following part.

Model experiments. To understand the influence of variations in C^{14} production rate on the C^{14} concentration in the atmosphere, it is necessary to consider the radiocarbon balance between the various reservoirs. *Craig* [1957] developed a model including the following reservoirs: atmosphere, biosphere, mixed layer of the ocean, and the deep sea. *De Vries* [1959] converted the model into an electric analog, which of course gives the same results but is easier to handle for some purposes.

According to the model, a variation in radiocarbon concentration of 2 per cent can be produced by a change in C^{14} production of about 25 per cent, assuming the duration of the production change to be of the order of 100 years. Considering the large fluctuations in neutron flux in the higher atmosphere during a single recent cycle, a difference of 25 per cent in average C^{14} production between periods with strong or weak sunspot maxima seems not to be impossible. Therefore we can conclude, provisionally, that the observed variations in radiocarbon concentration are of the same order of magnitude as those calculated from reasonable assumptions about variations in cosmic-ray activity.

Whereas a variation in average C^{14} production of 25 per cent gives a 2 per cent variation in radiocarbon concentration if the variation covers a period of the order of 100 years, short-time variations in production have much less influence on the C^{14} concentration. The normal variations during one sunspot cycle of 11 years are even attenuated by a factor of 75. As the possible fluctuations in production seem to vary by a factor of 2 during one sunspot cycle, the variation in radiocarbon concentration will be of the order of 1 per cent only. However, this factor of 2 is observed for the 1957 maximum, which is the strongest ever recorded, and it seems likely that fluctuations in radiocarbon concentration in the atmosphere larger than 0.5 per cent do not normally occur during one sunspot cycle. This is in accordance with the results in Groningen; measurements of the average C^{14} activity of a series of tree rings grown during consecutive years from either maxima or minima gave differences in activity in the right direction, but within the statistical error of 0.5 per cent.

As short time variations in production rate of C^{14} have much less influence upon the atmospheric C^{14} concentration than variations of longer duration, the sunspot curve will be different from the radiocarbon curve, even if one assumes a proportional relationship between the number of sunspots and the depression of the cosmic-ray activity. In order to study these differences in more detail, the electric model of de Vries was used, omitting the biosphere as a first approximation. To be able to use the model, the fluctuations in solar activity as given by Schove have to be converted into voltage fluctuations. This was done in the following way.

The edge of a circular sheet was carved so that the ordinary sunspot curve was transformed into a circular curve. The whole period covered by the sheet is 600 years. On the sheet, the years A.D. 2000 and 1400 coincide, while the connection between A.D. 1950 and 2000 is a straight line.

The sheet, with the circular sunspot curve carved on its edge, was mounted on the axis of a synchronous motor. While rotating, the sheet intercepts a part of a light beam striking along the edge of the sheet. The amount of light intercepted by the sheet depends on the area of the sheet passing the light beam. In this way light-intensity variations are produced that are inversely proportional to sunspot variations.

The light-intensity fluctuations can easily be converted into electric-current fluctuations by means of a photomultiplier. After amplification, voltage fluctuations proportional to sunspot activity are obtained. When the variations are led to an oscilloscope, the screen reproduces the sunspot curve.

The voltage fluctuations produced by the photomultiplier are supplied to the simplified electric model. The current supplied to the model corresponds to the C^{14} production in the atmosphere, while the voltages at the various points correspond to the concentrations in the several reservoirs. A more detailed discussion of the electric model has been given by *de Vries* [1959].

As soon as the steady state has been reached, a 1 per cent increase in current (C^{14} production) produces a 1 per cent increase in voltage (C^{14} concentration) in each reservoir. As most of the variations in sunspot activity are of the order of 100 years long, the real steady state cannot be reached and the variations at the various reservoirs appear to be much smaller than can be expected for a steady state. A 12 per cent variation in production rate, for the kind of variations discussed here, gives a 1 per cent variation in C^{14} concentration in the atmosphere, about $\frac{1}{2}$ per cent in the surface layer of the ocean and only $\frac{1}{10}$ per cent in the deep sea (for the simplified model).

Since the exchange rates between the various reservoirs are not exactly known, some experiments were performed to check the influence of these exchanges upon the ratio between production and concentration. When enlarging or decreasing either the resistor simulating the exchange between atmosphere and surface layer of the ocean or the resistor simulating the exchange between mixed layer and the deep sea by a factor of 2, the variation in the attenuation is only 30 per cent. So, even for widely different exchange rates, a variation in radiocarbon concentration of 1 per cent still corresponds to a variation in production rate of the order of 12 per cent, assuming that the production change lasts about 100 years.

In Figure 2 the variations in sunspot activity and radiocarbon concentration in the atmosphere, as obtained with the model, are compared with

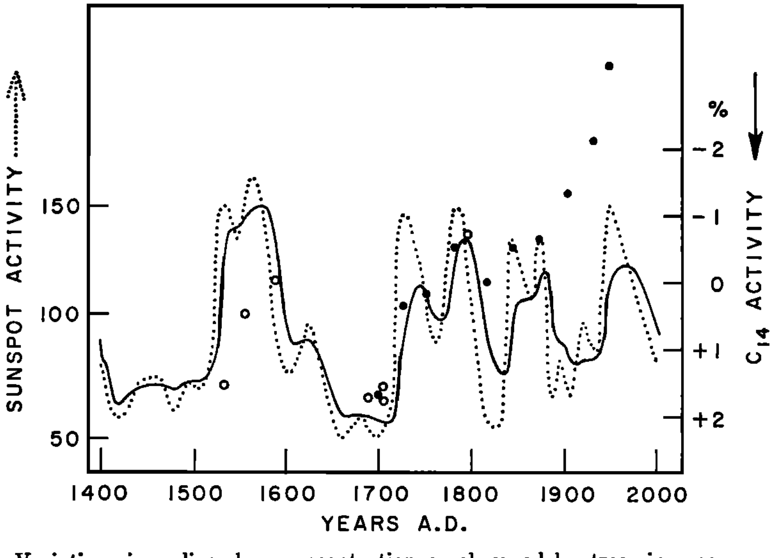

Fig. 2. Variations in radiocarbon concentration as observed by tree ring measurements [*de Vries*, 1958] and the same variations obtained from the model when an inversely proportional relationship between sunspot activity and C^{14} production is assumed.

each other. The phase shift between the curves appears to be small, about 10 to 15 years for the main variations. For comparison, both curves were drawn to the same scale, but in reality the variations in voltage (C^{14} concentration in the atmosphere) are on the average 12 times smaller than the variations in the current (C^{14} production rate). The unconnected points in the diagram give the variations in C^{14} activity as determined by *de Vries* [1958]. The curve giving the radiocarbon concentration in the atmosphere (black line) fits reasonably with the variations in radiocarbon concentration actually found. The deviation from the curve after about 1850 is due to the Suess effect. The curve of radiocarbon fluctuations gives about the same value for C^{14} activity in 1850 and in 1930. So, according to the curve, an appreciable correction of the Suess effect for the oscillations discussed here seems unnecessary.

Changes in isotopic equilibrium. Climatic changes correlated with sunspot activity [*Flint*, 1957] can produce changes in the isotopic equilibrium of the carbon reservoirs, thus leading also to variations in C^{14} activity in the atmosphere. As was shown by *de Vries* [1959] a 2 per cent variation in radiocarbon concentration can be explained by assuming a variation of exchange rate between the mixed layer of the ocean and the deep sea by a factor of 2. Whether such fluctuations are possible during the period discussed is not known. According to the calculations in the preceding paragraphs, the variations in cosmic-ray activity alone can account for the variations in radiocarbon activity observed, but it is not possible to exclude other causes; climatic changes may also be important.

Summary. Variations in cosmic-ray intensities, as observed in the higher atmosphere, will produce variations in the atmospheric C^{14} concentrations. The cosmic rays vary with the 11-year sunspot cycle. A comparison of radiocarbon content in tree rings with sunspot activity suggests some correlations between C^{14} concentration and sunspot activity. The order of magnitude of the observed variation in C^{14} concentration agrees with that calculated with the aid of a mechanical-electric model, making reasonable assumptions about variations in production rate. However, other variations, especially those in isotopic exchange rate associated with climatic changes are also possible. Conceivably both kinds of factors, those related to climatic changes and those affecting production rate, are important; in any case both are associated with sunspot activity.

References

Craig, H., The natural distribution of radiocarbon and the exchange time of carbon dioxide between atmosphere and sea, *Tellus, 9*, 1–17, 1957.

de Vries, Hl., Variation in concentration of radiocarbon with time and location on earth, *Proc. Koninkl. Ned. Akad. Wetenschap., B61*, no. 2, 1–9, 1958.

de Vries, Hl., Measurements and use of C^{14}, in *Researches in Geochemistry*, edited by P. H. Abelson, John Wiley & Sons, 169–189, 1959.

Flint, R. F., *Glacial and Pleistocene Geology*, John Wiley & Sons, New York, 495–500, 1957.

Schove, D. J., The sunspot cycle, 649 B.C. to A.D. 2000, *J. Geophys. Research, 60*, 127–146, 1955.

Simpson, J. A., The production of tritons and C^{14} in the terrestrial atmosphere by solar protons, *J. Geophys. Research, 65*, 1615–1616, 1960.

Willis, E. H., H. Tauber, and K. O. Münnich, Variations in the atmospheric radiocarbon concentration over the past 1300 years, Radiocarbon Supplement of the *Am. J. Sci., 2*, 1–4, 1960.

Winckler, J. R., Balloon study of high-altitude radiations during the International Geophysical Year, *J. Geophys. Research, 65*, 1331–1360, 1960.

(Manuscript received July 25, 1960; revised October 19, 1960.)