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STATISTICS OF THE AD RECORD OF CLIMATIC AND CARBON ISOTOPIC CHANGE

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ABSTRACT. The AD time series of $\Delta^{14}C$, $\delta^{13}C$, and cosmic ray fluxes, Q, were analyzed for similarities. Two cases of significant correlation between Q and tree-ring $\delta^{13}C$ were encountered, for which up to 25% of the variance can be attributed to changes in the tree's isotope fractionation that related to solar induced climatic changes. However, it is possible that the demonstrated correlation is fortuitous because actual climate proxy records generally do not correlate significantly with the Q record.

The history of $^{13}C/^{12}C$ and $^{14}C/^{12}C$ ratios in atmospheric CO_2 can be obtained from tree-ring cellulose because the carbon of the ring's cell walls is derived from the atmospheric CO_2 source. Isotope fractionation in the photosynthetic process adds another signal, and the measured carbon isotopic record in tree rings gives the sum-total of the isotope variations in atmospheric CO_2 (which can be of global and local origin), and the variability in isotope fractionation of the plant. By normalizing on a constant $^{13}C/^{12}C$ ratio a $^{14}C/^{12}C$ record can be derived independently of the tree's variability in isotope fractionation. However, the derivation of a $^{13}C/^{12}C$ record solely reflecting atmospheric change is more difficult because here the factors influencing the plant's isotope fractionation have to be known in detail (Stuiver, 1982).

Our research has yielded time series of $\delta^{13}C$ and $\Delta^{14}C$ change in tree rings during the AD interval. The ^{14}C record appears to reflect upper atmospheric ^{14}C production rate changes that are related to changes in magnetic properties of the solar wind and the earth's geomagnetic wind. From the $\Delta^{14}C$ record the production rate changes can be calculated through the use of carbon reservoir models (Stuiver and Quay, 1980; 1981a). The resulting record of solar variability, as reflected in cosmic-ray intensity change, has been compared with the available proxy data of climatic change without finding significant overall correlation (Stuiver, 1980).

As discussed, the $\delta^{13}C$ record reflects global changes in $\delta^{13}C$ ratios of atmospheric CO_2 on which are superimposed the changes induced by isotope fractionation, and possibly, by the changes in isotope ratio of the CO_2 in the local environment. The global, as well as the non-global isotope changes in the $\delta^{13}C$ record may be related to climatic change, eg, favorable growing conditions of *Sequoia giganteum* resulting in wide rings also yield high $\delta^{13}C$ values, and vice versa. If these growth changes are climatically related (as is often the case, see Fritts, 1976) then the $\delta^{13}C$ record includes a climatic signal. This raises the question whether there is any degree of similarity between the $\Delta^{14}C$ record (which is tied to solar variability and possibly climatic change) and the $\delta^{13}C$ records which may reflect climatic change. In the following discussion only the pre-AD 1850 portions of the isotope records are used, thus restricting the comparisons entirely to natural variation.

The power spectrum analysis employed here evaluates the non-randomness of the time series. The spectral estimates in the figures are the amplitudes of the cosine transforms of the serial correlation coefficients for the time series that have been smoothed by a 3-term weighted moving average with weights equal to ¼, ½, and ¼, respectively. The null spectrum is the Markov "red noise," the shape of which depends on the lag-one correlation coefficient (Mitchell, 1966). The 95 and 5% confidence limits are multiples of the "red noise" spectrum obtained from the percent points of χ^2/ν distribution for the calculated degrees of freedom ν.

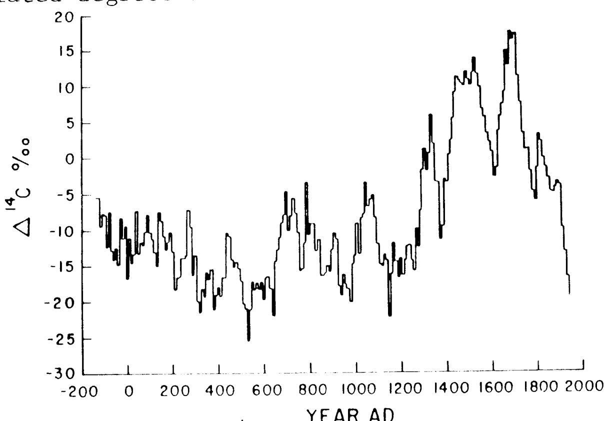

Fig 1. Atmospheric $\Delta^{14}C$ values, derived from decadal tree-ring samples from the Pacific Northwest and California.

The spectral properties of the $\delta^{13}C$ and $\Delta^{14}C$ time series vary with the time interval selected for each isotope, eg, the spectral distributions of the 1st and 2nd $\Delta^{14}C$ millennium AD record (fig 1) differ drastically. Whereas the AD 1000-1850 interval has two periodicities at ca 200 and 120 yr much beyond the 2σ level, the AD 1-1000 interval has significant power only at 105 and 42 yr (fig 2). The complete AD atmospheric $\Delta^{14}C$ record (AD 1-1850) has a periodicity that approaches the 2σ level at 42 yr only (fig 2). When extended to the BC period, there is again good evidence for a non-random 200-yr periodicity (Neftel, Oeschger, and Suess, 1981).

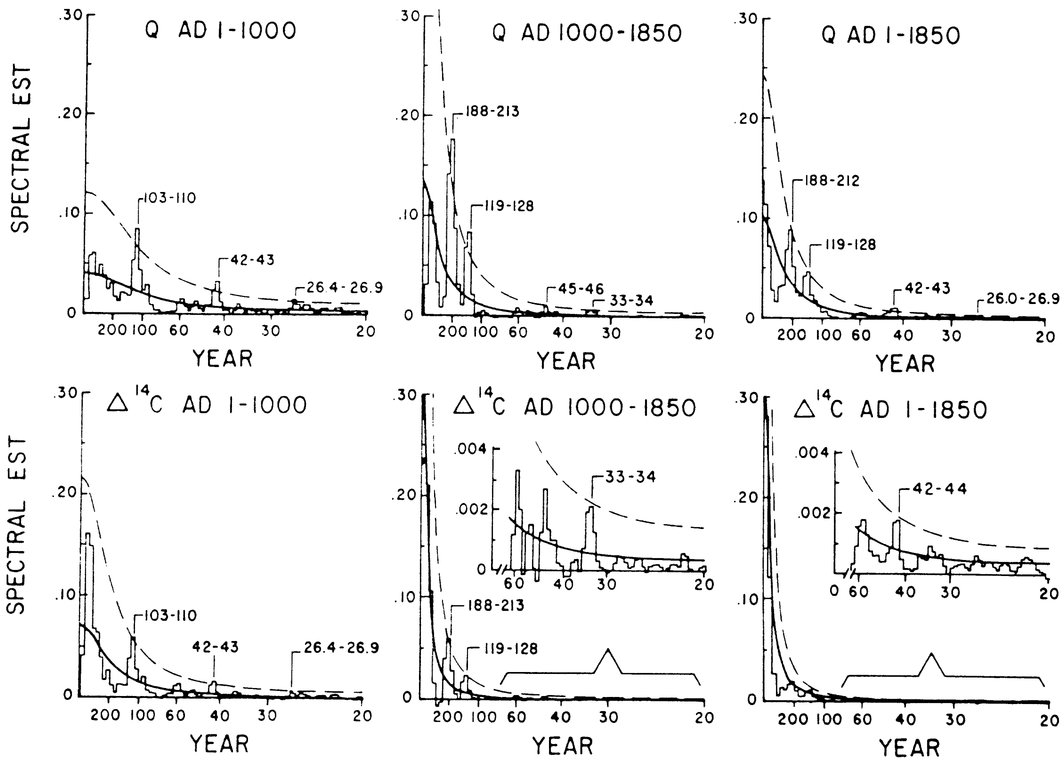

Fig 2. Spectral distribution of the decadal ^{14}C production rate record (Q) and $\Delta^{14}C$. The dashed line gives the 2σ confidence limit; the solid line gives the red noise continuum.

The records of production rate changes, Q, in the upper atmosphere, and the corresponding atmostpheric $\Delta^{14}C$ change, differ in spectral composition because the transport of ^{14}C between the various carbon reservoirs transforms the time-dependent properties. The calculated Q record, as obtained from carbon reservoir modeling (Stuiver and Quay, 1980; 1981b) with an oceanic eddy diffusion coefficient of 2.2cm^2/sec, yields the spectral distribution given in upper portion of figure 2. This spectral distribution depends somewhat on the model parameters, eg, a biospheric residence time of 20 yr instead of 60 yr would change the attenuation of the higher frequencies.

Whereas the tree-ring $\Delta^{14}C$ record for the complete AD period shows spectral power at 42 yr only, the Q record of solar change exhibits periodicities of ca 200, 120, and 42 yr. The actual Q record (fig 3) shows that the various maxima in ^{14}C production rate (isotope stages) are related to the sunspot minima some of which were named previously (ie, M-1 is the Maunder, S-1 the Sporer, M-2 the Wolf, and M-3 the Oort minimum).

From our stable isotope studies, the average $\delta^{13}C$ value of 10-yr samples relative to PDB is available for several trees (Stuiver, 1982; Stuiver et al, in press). Figures 4 and 5 give the longer $\delta^{13}C$ records and their spectral distributions. The four trees and the lengths of the records analyzed are: 1) a Bristlecone Pine (BP) from the ancient Bristlecone Pine Forest botanical area in Inyo National Forest, California (37° N Lat) for the AD 180 - 1850 interval; 2) two Sequoia trees, RC and CS, from the Sequoia National Park (RC) and the University of California Whittaker Forest (CS), both (37°N Lat). The RC tree spans the AD 230 - 1850 interval, and the CS tree, the AD 1280 - 1850 interval; 3) a Sitka Spruce from

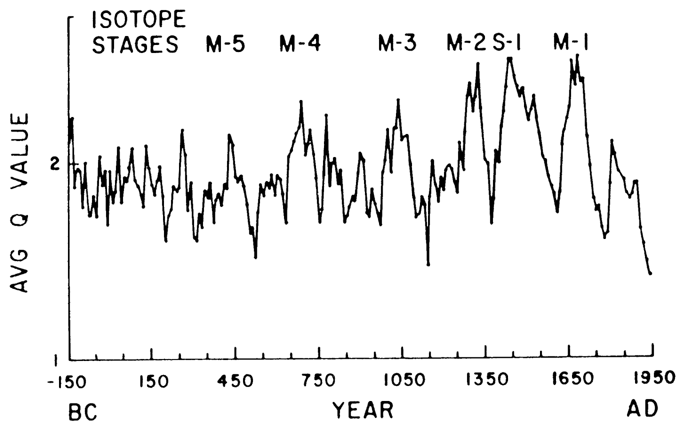

Fig 3. Calculated ^{14}C production rate Q of each decade in ^{14}C atoms/sec cm^2 (earth).

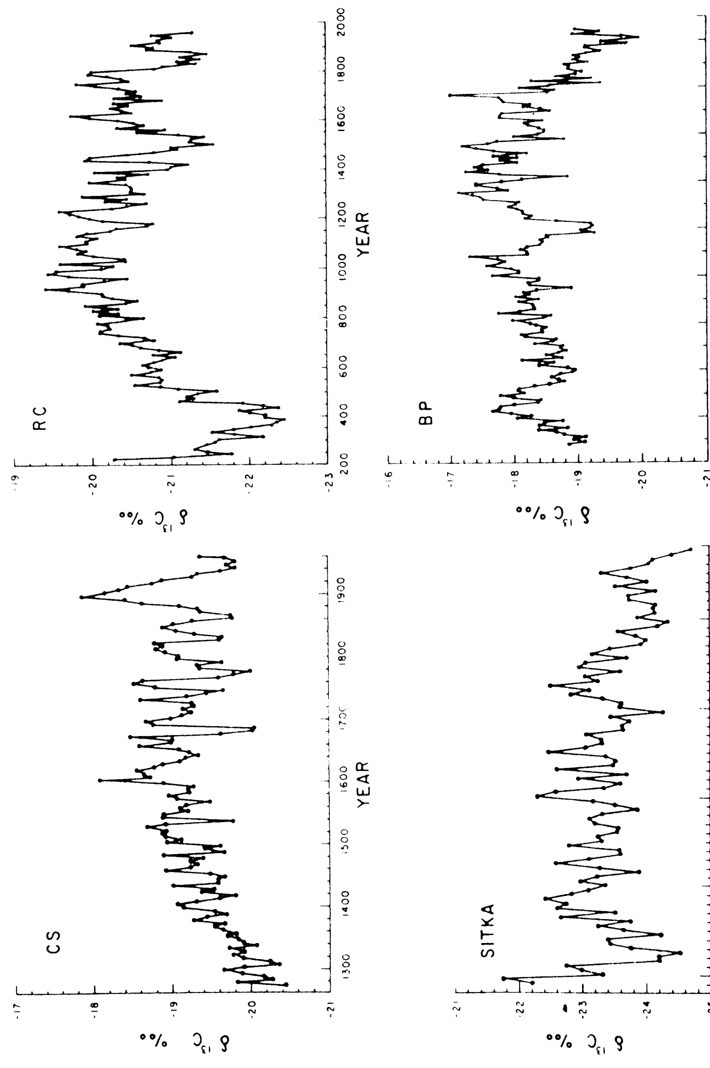

Fig 4. $\delta^{13}C$ decadal values, relative to PDB, of 2 sequoia's (CS and RC), a Sitka Spruce, and Bristlecone Pine (BP).

Bjorka Island, Alaska (57°N Lat) spanning the AD1490-1850 interval.

The spectra of the $\delta^{13}C$ time series (fig 5) contain few distinct features. The only statistically significant periods are 25 yr for Bristlecone Pine, and 30 yr for CS Sequoia. Evidently, common frequencies are absent in the $\delta^{13}C$ and $\Delta^{14}C$, or Q records.

The Q-$\delta^{13}C$ climate relationships can also be studied for randomness vs low frequency changes. The Q record, eg, is not a random series even though the properties are different for the two millennia. Randomness vs slow change was studied by analyzing auto-correlation coefficients. When a variable is generated entirely at random (in our case, by computer) the correlation coefficient of such a series when compared with itself is, of course, 1.0. However, when the series is compared with a lagged version of itself, the auto-correlation coefficients approach zero because the two compared series are not correlated. Figure 6A gives the auto-correlation record of a computer-generated random series, Figure 6b gives the auto-correlation plot of the Q data of the entire AD interval and figure 6c, of the current millennium. These Q auto-correlation diagrams differ strongly from the 6a curve, because the Q record contains an important non-random component.

Comparison of climate and Q records (Stuiver, 1980) revealed that only the oxygen isotope record of Camp Century, and the record of winter severity indexes in Russia, correlated at the 2 to 4% significance level with the Q record of the current millennium. Figures 6d and f give the auto-correlation diagrams of these climate records for the current millennium. The Russian winter severity index auto-correlation diagram shows much more randomness than the Q diagram, whereas the oxygen isotope auto-correlation diagram has similar features. Thus, the correlation between the record of solar variability, Q, and the Russian winter severity index may be coincidental.

Extending this analysis to $\delta^{13}C$ records yields figure 6e, g-i diagrams. Here Sitka Spruce and Bristlecone Pine $\delta^{13}C$ auto-correlation diagrams have features similar to the Q diagrams c and b that cover similar intervals. The Sequoia RC and CS auto-correlation plots are much broader because the $\delta^{13}C$ records of these trees include substantial long-term changes.

Correlation coefficients, r, were derived from cross-correlating the Q-record of solar variability and the $\delta^{13}C$ records (table 1). Correlation coefficients were also calculated by assuming a time lag between the Q and $\delta^{13}C$ curves of 100 yr or less. The maximum r values of this 100-yr interval are at time lags of 10 to 30 yr (table 1). These r_{max} values are not substantially different from the r values calculated through direct cross-correlation. If any relationship would exist between the Q and $\delta^{13}C$ curves, then a phase shift is restricted to a few decades only.

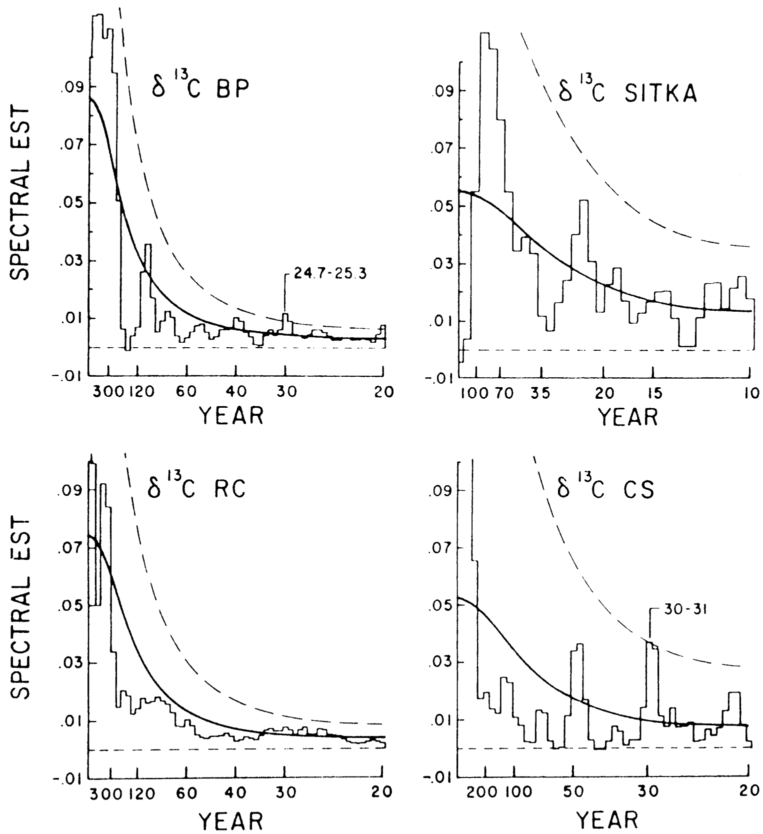

Fig 5. Spectral distribution of $\delta^{13}C$ records of figure 4. The dashed line gives the 2σ confidence level; the solid line gives the red noise continuum.

Because the Q record has substantial auto-correlation (it takes a 50 yr time lag for the auto-correlation coefficient to approach zero) the normal test of significance is no longer applicable. Auto-correlation reduces the number of independent observations used in interpreting the derived cross-correlations coefficients. The effective number N, of independent observations was calculated according to Quenouille (1952). N was subsequently used in deriving the probabilities of exceeding the values in table 1.

The r values derived from cross-correlating the $\delta^{13}C$ time series of Bristlecone Pine, and RC Sequoia, with the Q series are small despite the similar auto-correlation plot of BP (table 1), and indicate lack of relationship between global ^{14}C production and the $\delta^{13}C$ records of these trees. The correlation does not improve when the more recent AD 1400 - 1850

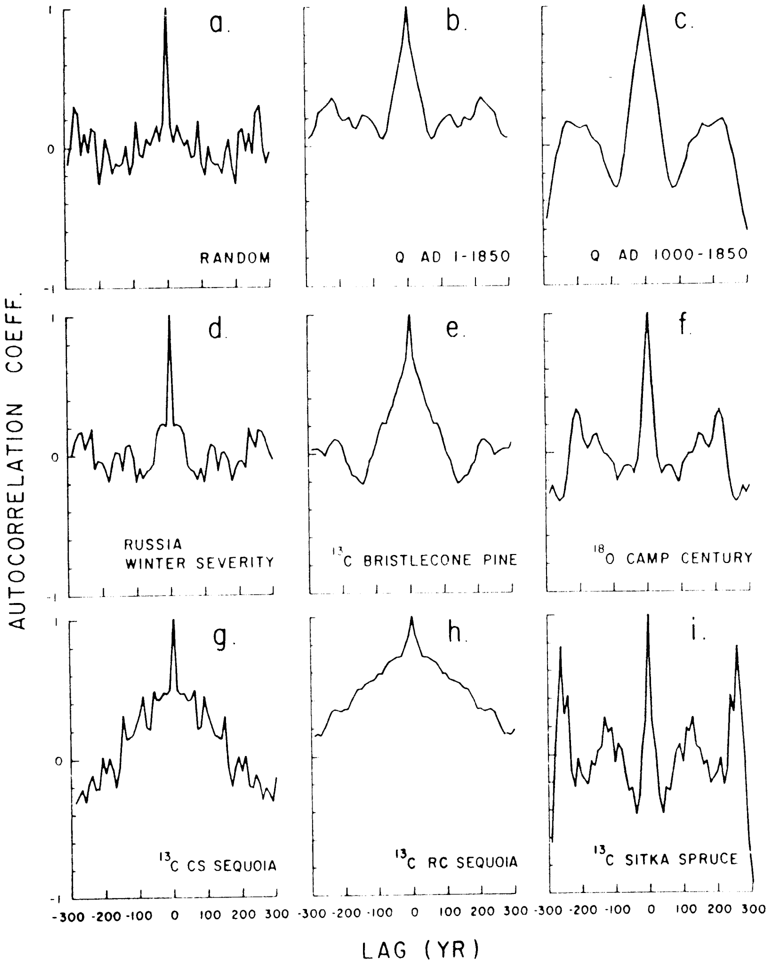

Fig 6. Autocorrelation coefficients of a. a random series, b-c. the ^{14}C production rate Q, d. Russian winter severity index (AD 1100-1850, e. decadal $\delta^{13}C$ values of Bristlecone Pine, f. $\delta^{18}O$ values of the Camp Century core (AD 1200-1850), and g-i. decadal $\delta^{13}C$ values of 2 sequoia's and a Sitka spruce.

TABLE 1. Correlation coefficients, r, derived from cross-correlating ^{14}C production rate, Q, record (fig 3) with $\delta^{13}C$ records listed below. All records have one measured (or calculated for the Q record) value per decade.

Locality, age	Species	r	Δt (yr)	r_{max}*	Δt (yr)	r_{max}*
Inyo Natl Forest (37°N Lat) AD 180-1850	Pinus aristata	0.117 (44%)	20	0.13 (39%)	-20	0.122 (42%)
Sequoia Natl Park, (37°N Lat) AD 230-1850	Sequoiadendron giganteum	0.15 (39%)	10	0.15 (39%)	-30	0.20 (25%)
Whittaker Forest (37°N Lat) AD 1280-1850	Sequoiadendron giganteum	0.39 (12%)	20	0.52 (3%)	0	0.39 (12%)
Bjorka (57°N Lat) AD 1490-1850	Picea sitchensis	0.38 (3%)	0	0.38 (3%)	0	0.38 (3%)

* Values are obtained by assuming 1) $\delta^{13}C$ variables precede Q changes, 2) Q changes precede $\delta^{13}C$ changes. The probabilities of exceeding the r values in a random series are in parenthesis. r_{max} values are only listed for time lags of 100 yr or less.

interval is considered for the above trees (significance levels respectively, 51 and 76% for zero lag).

The two remaining $\delta^{13}C$ records, of CS Sequoia and Sitka Spruce appear to correlate with the Q record at the 12 and 3% significance levels. While lagging the ^{13}C record by 20 yr, the significance level of the CS correlation also approaches 3% (table 1). This suggests, at least for two of our $\delta^{13}C$ records, a relationship between $\delta^{13}C$ change and ^{14}C production rate Q for the AD 1300 - 1850 interval.

The r value of global atmospheric $\Delta^{14}C$ and tree-ring $\delta^{13}C$ are 0.06 and 0.30 for Sitka Spruce and CS Sequoia, respectively. For a ±100 yr lag interval, the r values are, respectively, in the -.26 to .22 and -.41 to .24 range. Significant correlations are absent, especially since the $\Delta^{14}C$ record has substantial auto-correlation.

The absence of a direct tie between global $\Delta^{14}C$ and tree-ring $\delta^{13}C$ furthers the idea that the $\Delta^{14}C$ changes are not caused by large changes in carbon reservoir parameters, eg, changes caused by ocean-atmosphere exchange rate changes should influence the distribution of both isotopes in a similar manner.

The 3% significance level correlation of the $\delta^{13}C$ Sitka and CS record (for the latter, admittedly, with a 20-yr lag) and the Q record is interesting. For random time series, 1 in 20 comparisons should yield by chance alone a 5% or better significance level. Of actual comparisons, 2 out of 4 are beyond the 5% level. Evidently, for Sitka Spruce and CS Sequoia, a relationship between climatically controlled $\delta^{13}C$ and the global record of solar change, as found in the Q change, appears possible. Such an imprint of solar-induced climatic change could explain 16 to 25% of the variance in the $\delta^{13}C$ record of Sitka Spruce and CS Sequoia, respectively. Whether such a climatic change tied to solar variability is indeed possible remains to be seen. More direct comparisons with climate proxy records (Stuiver, 1980) generally do not favor a relationship between the Q record and climate.

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