Cosmic Rays, Carbon Dioxide and Climate

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Several recent papers have applied correlation analysis to climate-related time series in the hope of finding evidence for causal relationships. For a critical discussion of correlations between solar variability, cosmic rays and cloud cover see [*Laut*, 2003].

A prominent new example is a paper by [*Shaviv and Veizer*, 2003] (henceforth called SV03), which claims that fluctuations in cosmic ray flux reaching the Earth can explain 66% of the temperature variance over the past 520 million years (520 Myr), and that the sensitivity of climate to a doubling of CO_2 is smaller than previously estimated.

Shaviv and Veizer's paper was accompanied by a press release titled "Global warming not a man-made phenomenon", in which Shaviv is quoted stating: "*The operative significance of our research is that a significant reduction of the release of greenhouse gases will not significantly lower the global temperature, since only about a third of the warming over the past century should be attributed to man*".

We here present a critical appraisal of the methods and conclusions of SV03.

Reconstructing cosmic ray fluxes

The starting point of SV03 is a reconstruction of cosmic ray fluxes over the past 1,000 Myr based on 50 iron meteorites and a simple model estimating cosmic ray flux (CRF) induced by the Earth's passage through Galactic spiral arms ([*Shaviv*, 2002; *Shaviv*, 2003]). About 20 of the meteorites, making four clusters, date from the past 520 Myr, the time span analysed in SV03. The meteorites are dated by analysing isotopic changes in their matter due to cosmic ray exposure (CRE dating [*Eugster*, 2003]). An apparent age clustering of these meteorites is then interpreted not as a collision-related

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clustering in their real ages but as an indication of fluctuations in cosmic ray flux (CRF).

One difficulty with this interpretation is that variations in CRF intensity would equally affect all types of meteorites. Instead, the ages of different types of iron meteorites cluster at different times [*Wieler*, 2002]. Hence, most specialists on meteorite CRE ages interpret the clusters as the result of collision processes of parent bodies, as they do for stony meteorites (ages ≤ 130 Myr) to which more than one dating method can be applied.

Another problem of the CRF reconstruction is the presumption of "periodicity" of the clusters. The time spans between the clusters' gaps, which correspond to high CRF in their theory, are roughly 90, 90, 140, 130, 190, 140 Myr (Fig. 4 of [*Shaviv*, 2003]). The claim that these data support a periodicity of 143±10 Myr seems not obvious. The passage through the four galactic arms should be a regular process; the high variability of the age gaps is not addressed.

The CRF model is based on the assumption that cosmic ray density should be concentrated in the Galactic spiral arms, with a time lag of peak CRF of about 15 Myr behind the spiral arm passage. CRF is computed by a simple diffusion model with several free parameters. These parameters are constrained by 'observational constraints', including the meteorite data. These constraints are very weak; the crucial cosmic ray diffusion coefficient can only be constrained to within two orders of magnitude.

Moreover, even the best-fit CRF model does not fit the meteorite data well. For the time span analysed in SV03, the cluster gaps are located near 100 Myr, 190 Myr, 280 Myr and 420 Myr BP (Fig. 4 of [*Shaviv*, 2003]); they are supposed to coincide with CRF maxima which the 'best fit' model locates at about 30 Myr, 170 Myr, 360 Myr and 470 Myr BP. This is hardly a good agreement, with an rms deviation of 60 Myr. Agreement of the three CRF minima (at ~80 Myr, 250 Myr, 420 Myr BP) with the age clusters (at ~140 Myr, 250 Myr, 360 Myr BP) is hardly better, with two of the three clusters off by almost half a period. The only apparent similarity between the CRF model and the meteorite data is the *average* of the periods. The large uncertainty about the timing of spiral arm crossings and the associated CRF maxima is corroborated by the fact that another recent paper ([*Leitch and Vasisht*, 1998]), which uses the spiral arm crossings to explain biological extinctions, places these crossings at completely different times.

The final parameter choice of the CRF model shown in Fig. 10 of [*Shaviv*, 2003] is that "which best fits the ice age epochs", i.e., the cosmic ray model has already been fitted to climate data. This circular reasoning compromises the significance of any subsequent correlation with climate data.

Correlating cosmic ray fluxes to surface temperature

Next, SV03 correlate a CRF reconstruction with a reconstruction of sea surface temperature based on oxygen isotope data from calcite shells from various low-latitude sites. The temperature proxy data were detrended and smoothed with a 50 Myr window to emphasise variations on the ~150 Myr period of the CRF model. The CRF model used in SV03 (shown in Fig. 2 of SV03 as a blue line) is not the same as either of the two different CRF curves shown in [*Shaviv*, 2003], even though this publication is given as its source. The CRF curves shown in Fig. 7 and Fig. 10 of [*Shaviv*, 2003] have a CRF maximum near 360 Myr, while that shown in SV03 has a maximum near 320 Myr. [*Shaviv*, 2003] argues that such a shift of this peak is within the observational uncertainty of the position of the Norma Galactic spiral arm and would “increase the agreement” with climate data.

SV03 then arbitrarily change the time scale in the reconstruction to obtain yet another CRF curve (the red curve in Fig. 2 of SV03), which they call “fine tuned to best fit the low-latitude temperature”. This third tuning step shifts the third CRF maximum by another ~20 Myr to near 300 Myr. This CRF maximum has thus been shifted by ~60 Myr, almost half a period, compared to those shown in [*Shaviv*, 2003].

The correlation between this final cosmic ray curve and the temperature record is r = 0.81 for an “explained variance” of 66%. However, the CRF curve before this final “fine-tuning” (i.e., the less-tuned blue curve in Fig. 2 of SV03) explains only 30% of the variance, which is statistically indistinguishable from zero.

We thus find that there is no significant correlation of the CRF curve from Shaviv’s model and the temperature curve of Veizer, even after one of the four CRF peaks was arbitrarily shifted by 40 Myr to improve the fit to the temperature curve. There also is no significant correlation between the original meteorite data and the temperature reconstruction. The explained variance claimed by SV03 is the maximum achievable by optimal smoothing of the temperature data and by making several arbitrary adjustments to the cosmic ray data (within their large uncertainty) to line up their peaks with the temperature curve.

Regression of CO_2 and temperature

The final argument of SV03 – that CO_2 has a smaller effect on climate than previously thought – is based on a simple regression analysis of smoothed temperature and CO_2 reconstructions. SV03 conclude that the effect of a doubling of atmospheric CO_2 concentration on tropical sea surface temperatures (SST) is likely to be 0.5ºC (up to 1.9ºC at 99% confidence), with global mean temperature changes about 1.5 times as large. Thus they claim that the climate sensitivity to 2xCO_2 is around 0.75 ºC, outside the Intergovernmental Panel on Climate Change range of 1.5-4.5 (misquoted as 5.5ºC in SV03) [*IPCC*, 2001]. Note, however, that their maximum global sensitivity of 2.9ºC lies well within the accepted range.

A critique of the CO_2 and temperature reconstructions used in SV03 will be published by Royer et al [in press], who correct the Veizer et al □^{18}O record for the effect of changing pH. This effect has been demonstrated in culture [*Spero et al.*, 1997] and explained theoretically [*Zeebe*, 1999; *Zeebe*, 2001]. The result is a corrected climate record that no longer follows the cosmic ray model but correlates well with the Geocarb III CO_2 reconstruction.

SV03 challenge the credibility of the CO_2 reconstructions by showing two divergent alternatives to the well-known Geocarb III model, by U. (not R.) Berner (not documented in the scientific literature) and by [*Rothman*, 2002].

SV03 argue that the disagreement between the reconstructions reveals them to be in need of „validation“, but ignore the large literature of paleosol, stomatal, and carbon and boron isotopic data, which support the Geocarb reconstruction [Royer et al, in press].

Irrespective of the data quality, the simple regression method of SV03 is unsuitable to estimate the climate sensitivity to a CO_2 doubling. The main reasons are that *(i)* other forcing and feedback factors may co-vary in a statistically dependent way with CO_2 and cannot be separated, *(ii)* the operation of some climate feedbacks depends on the time scale considered, and *(iii)* the strength of climate feedbacks depends on the mean climate.

Over a decade ago, [*Lorius et al.*, 1990] used the high-quality records of temperature and CO_2 variations from ice cores to derive information on climate sensitivity. These authors had reliable data available and carefully considered the above caveats. Concerning *(i)*, [*Lorius et al.*, 1990] recognised that CO_2 and methane concentrations co-vary, so that only the joint effect of both gases can be derived by regression. They accounted for the known orbital forcing and also considered other possible feedbacks, such as the aerosol loading of the atmosphere. They further distinguished slow and fast feedbacks (caveat *(ii)*). The growth and decay of continental ice sheets represents a slow feedback operating over millennia; if one is concerned with the more rapid response of the climate to CO_2, ice sheets have to be accounted for as a major forcing.

In contrast, SV03 accounted for none of these caveats. Concentrations of other greenhouse gases, which may have co-varied with CO_2 on the multi-million-year time scale, are not known, and neither is the aerosol loading of the atmosphere or the external forcing of the climate changes on this time scale. Likewise, it is not known which physical, geochemical or biological feedbacks may operate, and at what magnitude, on such long time scales.

[*Lorius et al.*, 1990] concluded from their analysis that climate sensitivity to a doubling of CO_2 is 3-4ºC, in good agreement with independent estimates based on the physical understanding of CO_2 forcing and relevant feedbacks as coded in models. Note that the primary driver of glacial cycles is the Milankovich orbital forcing while CO_2 acts as an amplifying feedback; this in no way questions the effect of CO_2 on temperature.

The dependence of climate sensitivity on the mean state (caveat (*iii)*) cannot be avoided, but it is a more serious problem for the time period considered by SV03 with conditions very different from the modern climate system. Positions of continents shifted, ocean currents took a different course, and estimated CO_2 levels were between twice and ten times of present values during most of this time. Little is known about the feedbacks operating on these time scales and for high CO_2 climates. There are good reasons to assume that important amplifying feedbacks, such as the snow albedo feedback, become much weaker in warmer climates, which would result in an underestimation of climate sensitivity to CO_2 doubling in such a regression.

Conclusions

Two main conclusions result from our analysis of SV03. The first is that the correlation of cosmic ray flux (CRF) and climate over the past 520 Myr appears to not hold up under scrutiny. Even if we accept the questionable assumption that meteorite clusters give information on CRF variations, we find that the evidence for a link between CRF and climate amounts to little more than a similarity in the average periods of the CRF variations and a heavily smoothed temperature reconstruction. Phase agreement is poor. The authors applied several adjustments to the data to artificially enhance the correlation. We thus find that the existence of a correlation has not been convincingly demonstrated.

Our second conclusion is independent of the first. Whether there is a link of CRF and temperature or not, the authors' estimate of the effect of a CO_2-doubling on climate is highly questionable. It is based on a simple and incomplete regression analysis which implicitly assumes that climate variations on time scales of millions of years, for different configurations of continents and ocean currents, for much higher CO_2 levels than at present, and with unaccounted causes and contributing factors, can give direct quantitative information about the effect of rapid CO_2 doubling from pre-industrial climate. The complexity and non-linearity of the climate system does not allow such a simple statistical derivation of climate sensitivity without a physical understanding of the key processes and feedbacks. We thus conclude that [*Shaviv and Veizer*, 2003] provide no cause for revising current estimates of climate sensitivity to carbon dioxide.

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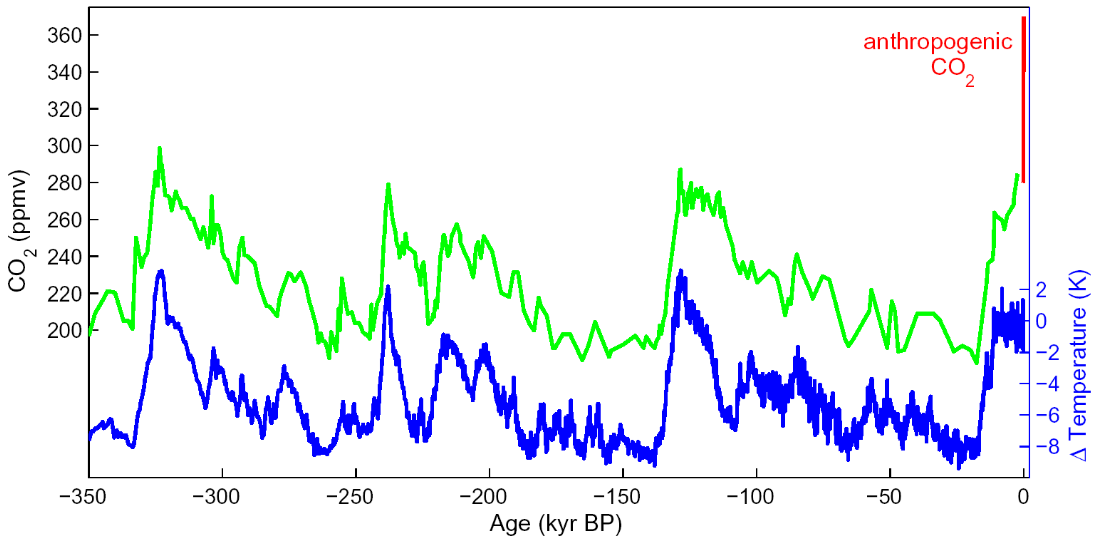

Figure 1. Records of CO_2 (green) and temperature (blue) over the past 350,000 years from the Vostok ice core, after [*Petit et al.*, 1999]. The recent anthropogenic rise in CO_2 ([*IPCC*, 2001]) is marked in red.