Cosmic rays, carbon dioxide, and climate

Stefan Rahmstorf, David Archer, Denton Ebel, Otto Eugster, Jean Jouzel, Douglas Maraun, Urs Neu, Gavin Schmidt, Jeff Sever-Inghaus, Andrew Weaver, et al.

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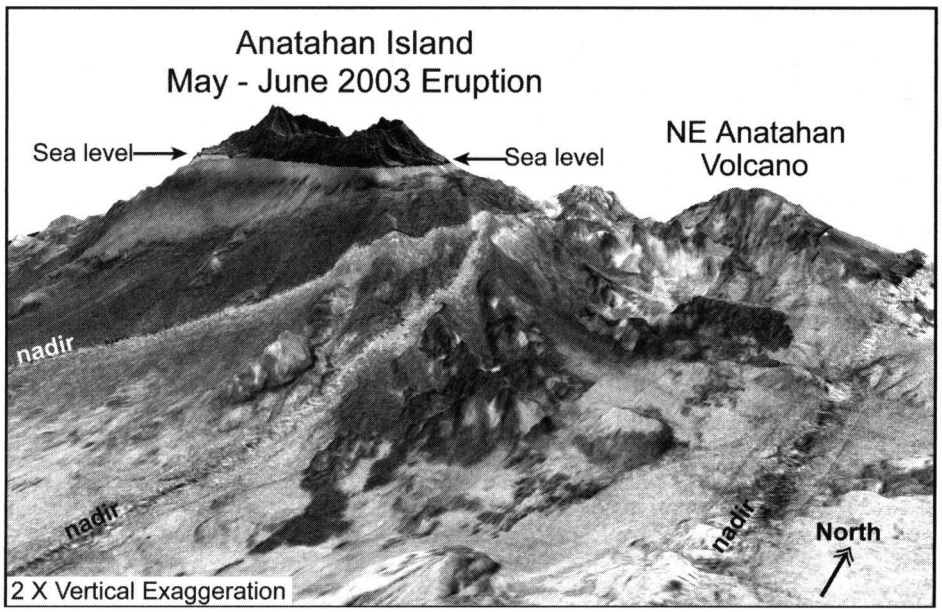

Fig. 3. MR1 sidescan sonar backscatter imagery (16-m grid) draped over EM300 and SB2000 multibeam bathymetry (35-m grid) is shown in the vicinity of Anatahan Island (location on Figure 1). The view is looking north-northwest toward southern flank of the Anatahan Island. Darker shades represent higher backscatter values. Tracks (linear bands marked as "nadir") spaced at approximately 9-km spacing in foreground. Anatahan Island is 9 km in length. The SB2000 data was collected by R. Dziak. The digital elevation model of Anatahan Island was created by Steve Schilling (U.S. Geological Survey) and geo-referenced with control points provided by Frank Trusdell (U.S. Geological Survey).

Author Information

R. W. Embley, Pacific Marine Environmental Laboratory, NOAA, Newport, Ore.; E. T. Baker, Pacific Marine Environmental Laboratory, NOAA, Seattle, Wash.; W. W. Chadwick, Jr., CIMRS, Oregon State University, Newport; J. E. Lupton, Pacific Marine Environmental Laboratory, NOAA, Newport, Ore.; J. A. Resing, JISAO, NOAA/PMEL, Seattle, Wash.; G. J. Massoth, Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand; and K. Nakamura, National Institute of Advanced Industrial Science and Technology, Ibaraki, Japan

For additional information, contact R. W. Embley; E-mail: robert.w.embley@noaa.gov

FORUM

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], which claims that fluctuations in cosmic ray flux reaching the Earth can explain 66% of the temperature variance over the past 520 m.y., and that the sensitivity of climate to a doubling of CO_2 is less 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 as 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."

Here we present a critical appraisal of the methods and conclusions of *Shaviv and Veizer* [2003].

Reconstructing Cosmic Ray Fluxes

The starting point of *Shaviv and Veizer* [2003] is a reconstruction of cosmic ray fluxes over the past 1000 m.y. 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, 2003]. About 20 of the meteorites, making four clusters, date from the past 520 m.y., the time span analyzed in *Shaviv and Veizer* [2003]. The meteorites are dated by analyzing 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 clustering in their real ages, but as an indication of fluctuations in cosmic ray flux.

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 m.y.), 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 m.y. (Figure 4 of *Shaviv* [2003]). The claim that these data support a periodicity of 143 ± 10 m.y. does not seem 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 m.y. 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 analyzed in *Shaviv and Veizer* [2003], the

cluster gaps are located near 100 m.y., 190 m.y., 280 m.y., and 420 m.y. (Figure 4 of *Shaviv* [2003]); they are supposed to coincide with CRF maxima that the "best fit" model locates at about 30 m.y., 170 m.y., 360 m.y., and 470 m.y. This is hardly a good agreement, with an rms deviation of 60 Ma. Agreement of the three CRF minima (at ~ 80 m.y., 250 m.y., and 420 m.y.) with the age clusters (at ~140 m.y., 250 m.y., and 360 m.y.) 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"; that is, 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, *Shaviv and Veizer* [2003] 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-m.y. window to emphasize variations on the ~150 m.y. period of the CRF model. The CRF model used in *Shaviv and Veizer* [2003] (shown in Figure 2 of *Shaviv and Veizer* [2003] 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 Figures 7 and 10 of *Shaviv* [2003] have a CRF maximum near 360 m.y., while that shown in *Shaviv and Veizer* [2003] has a maximum near 320 m.y. *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.

Shaviv and Veizer [2003] then arbitrarily change the time scale in the reconstruction to obtain yet another CRF curve (the red curve in Figure 2 of *Shaviv and Veizer* [2003]), which they call "fine tuned to best fit the low-latitude." This third tuning step shifts the third CRF maximum by another ~ 20 m.y. to near 300 m.y. This CRF maximum has thus been shifted by ~ 60 m.y., 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 Figure 2 of *Shaviv and Veizer* [2003]) explains only 30% of the variance, which is statistically indistinguishable from zero.

We thus find that there is no significant correlation between the CRF curve of Shaviv's model and the temperature curve of Veizer, even after one of the four CRF peaks was arbitrarily shifted by 40 m.y. 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 *Shaviv and Veizer* [2003] 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.

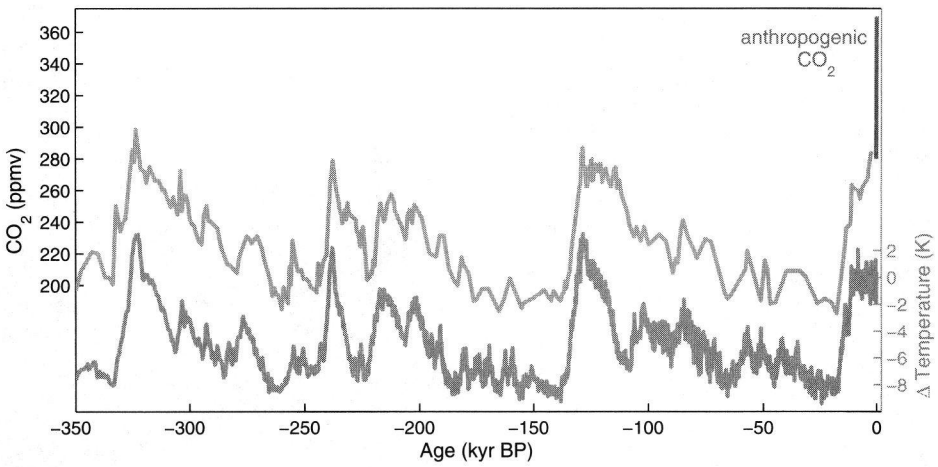

Fig. 1. Records of CO_2 (green) and temperature (blue) over the past 350,000 years from the Vostok ice core are shown, after Petit et al. *[1999]. Part of these data were used by* Lorius et al. *[1990] to estimate climate sensitivity. The recent anthropogenic rise in CO_2 [*IPCC, *2001] is marked in red. Original color image appears at back of volume.*

Regression of CO_2 and Temperature

The final argument of *Shaviv and Veizer* [2003]—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. *Shaviv and Veizer* [2003] conclude that the effect of a doubling of atmospheric CO_2 concentration on tropical sea surface temperatures (SST) is likely to be 0.5°C (up to 1.9°C 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 ~ 0.75°C, outside the Intergovernmental Panel on Climate Change range of 1.5–4.5°C (misquoted as 5.5°C in *Shaviv and Veizer* [2003]) [*IPCC,* 2001]. Note, however, that their maximum global sensitivity of 2.9°C lies well within the accepted range.

A critique of the CO_2 and temperature reconstructions used in *Shaviv and Veizer* [2003] will be published by *Royer et al.* [2004], who correct Veizer's $\delta^{18}O$ record for the effect of changing pH. This effect has been demonstrated in culture [*Spero et al.,* 1997] and explained theoretically [*Zeebe,* 1999, 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.

Shaviv and Veizer [2003] challenge the credibility of the CO_2 reconstructions by showing two divergent alternatives to the well-known Geocarb III model, by U. Berner (not documented in the scientific literature), and by *Rothman* [2002]. *Shaviv and Veizer* [2003] 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.*, 2004].

Irrespective of the data quality, the simple regression method of *Shaviv and Veizer* [2003] is unsuitable for estimating 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 (Figure 1) to derive information about climate sensitivity. These authors had reliable data available and carefully considered the above caveats. Concerning (i), *Lorius et al.* [1990] recognized 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 represent 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, *Shaviv and Veizer* [2003] accounted for none of these caveats. Concentrations of other greenhouse gases, which may have co-varied with CO_2 on the multimillion-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 3–4°C, 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 *Shaviv and Veizer* [2003] 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 two and 10 times 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.

Conclusion

Two main conclusions result from our analysis of *Shaviv and Veizer* [2003]. The first is that the correlation of CRF and climate over the past 520 m.y. 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 that 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 CO_2.

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—Stefan Rahmstorf, Potsdam Institute for Climate Impact Research, Germany; David Archer, University of Chicago, Ill.; Denton S. Ebel, American Museum of Natural History, N.Y.; Otto Eugster, University of Bern, Switzerland; Jean Jouzel, Institut Pierre Simon Laplace/LSCE, Saclay, France; Douglas Maraun, Potsdam University, Germany; Urs Neu, Swiss Academy of Sciences, Bern; Gavin A. Schmidt, NASA GISS and Center for Climate Systems Research, Columbia University, N.Y.; Jeff Severinghaus, Scripps Institution of Oceanography, San Diego, Calif.; Andrew J. Weaver, University of Victoria, B.C., Canada; and Jim Zachos, University of California, Santa Cruz

About AGU

Dahlen Receives 2003 Inge Lehmann Medal

Francis A. Dahlen, Jr. was awarded the Lehmann Medal at the AGU Fall Meeting Honors Ceremony, which was held on 10 December 2003, in San Francisco, California. The medal honors "outstanding contributions to the understanding of the structure, composition, and dynamics of the Earth's mantle and core."

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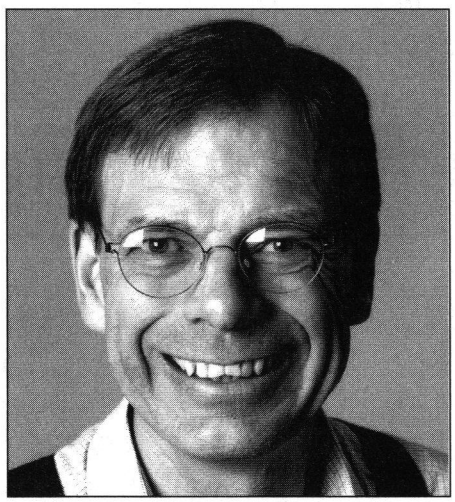
Citation

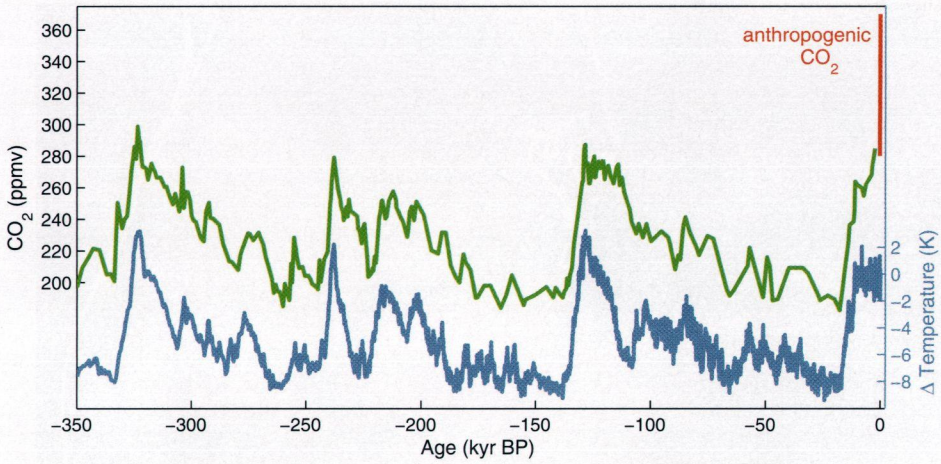
"I feel honored and pleased to cite my friend and Princeton colleague Tony Dahlen for the Inge Lehmann Medal. Given Tony's wide range of important contributions, there is actually a choice of AGU honors one might cite him for; his influence extends well beyond those fields that are primarily associated with the Lehmann Medal.

"Tony started his scientific journey as an undergraduate at Caltech. By the time he moved on to graduate studies with George Backus and Freeman Gilbert at Scripps he was already applying his many talents to geophysics. He soon pioneered a series of papers on normal modes that represent the first substantial step away from Earth's spherical symmetry. In fact, all of the current research on the use of low-frequency seismic data for the determination of the Earth's three-dimensional structure is based on this early work, its extension to an inverse problem, and subsequent research with Martin Smith and John Woodhouse. His interest in the theory of global tomography has survived until this day: recently he developed a very elegant and efficient theory to include the frequency-dependent effects of diffraction into body wave tomography, a theoretical improvement that was almost immediately



rewarded by the imaging of a large number of mantle plumes. These represent the first concrete seismological evidence that many hot spots originate deep in the mantle, confirming Jason Morgan's long-standing hypothesis.

"Tony's research into low-frequency seismology led him to investigate the rotation of the Earth; he discovered the excitation mechanism for the Chandler wobble and he quantified the



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