

# Dynamical evidence for causality between galactic cosmic rays and interannual variation in global temperature

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As early as 1959, it was hypothesized that an indirect link between solar activity and climate could be mediated by mechanisms controlling the flux of galactic cosmic rays (CR) [Ney ER (1959) *Nature* 183:451–452]. Although the connection between CR and climate remains controversial, a significant body of laboratory evidence has emerged at the European Organization for Nuclear Research [Duplissy J, et al. (2010) *Atmos Chem Phys* 10:1635–1647; Kirkby J, et al. (2011) *Nature* 476(7361):429–433] and elsewhere [Svensmark H, Pedersen JOP, Marsh ND, Enghoff MB, Uggerhøj UI (2007) *Proc R Soc A* 463:385–396; Enghoff MB, Pedersen JOP, Uggerhøj UI, Paling SM, Svensmark H (2011) *Geophys Res Lett* 38:L09805], demonstrating the theoretical mechanism of this link. In this article, we present an analysis based on convergent cross mapping, which uses observational time series data to directly examine the causal link between CR and year-to-year changes in global temperature. Despite a gross correlation, we find no measurable evidence of a causal effect linking CR to the overall 20th-century warming trend. However, on short interannual timescales, we find a significant, although modest, causal effect between CR and short-term, year-to-year variability in global temperature that is consistent with the presence of nonlinearities internal to the system. Thus, although CR do not contribute measurably to the 20th-century global warming trend, they do appear as a nontraditional forcing in the climate system on short interannual timescales.

climate variability | cosmic rays | global temperature | causality | convergent cross mapping

The basic principles behind a possible connection between galactic cosmic rays (CR) and global temperature (GT) are as follows: It has been known since the invention of the cloud chamber in 1911 by Charles Thomson Rees Wilson that ionizing radiation leads to atmospheric cloud nucleation. Although the prime source of ionizing radiation in the global troposphere is CR, the flux of CR reaching the troposphere depends on the solar wind. The solar wind is a stream of ionized gases that blows outward from the Sun, and its intensity varies strongly with the level of surface activity on the Sun. The Earth's magnetic field shields the planet from much of the solar wind, deflecting that wind like water around the bow of a ship. When solar activity is great, the solar wind is strong, swiping away CR arriving at the top of the atmosphere. These CR are hypothesized to affect cloud formation and cloudiness, and therefore GT. The net radiative effect of cloudiness depends on the difference between incoming solar radiation and outgoing long-wave radiation. Increased cloudiness in the upper troposphere reduces outgoing long-wave radiation, thereby resulting in warming of the planet. Increased cloudiness in the lower troposphere causes less incoming radiation, and therefore cooling of the planet. Data suggest (6) that the amount of CR is positively correlated with the amount of low-level clouds but has no effect on middle- or high-level clouds. Although this is still an open question (7, 8),

the reduction in flux in CR in times of high solar activity is hypothesized to result in less cloud nucleation and fewer cloud condensation nuclei, and consequently, reduced low-level cloud amounts. This, in turn, leads to a higher solar radiation flux at the Earth's surface, and warmer temperatures. Conversely, a weaker solar wind results in cooler temperatures. The actual chemical processes and reactions involved in this problem are complex, but a growing body of experimental and theoretical work has uncovered a chemical pathway by which CR ionization may increase nucleation rates to levels appropriate for cloud condensation nuclei (2–5, 9–11 and references therein). This suggests a superficially simple network linking the Sun, CR, and global climate, with the interaction between the Sun and CR having a potential influence on the climate system. However reasonable this may be, as described in a 2006 review (12), “The suggested mechanisms are, however, too complex to evaluate meaningfully at present.”

## Data Analysis and Results

In this article, we use a recently developed method to examine the causal connection, as it exists, between CR and GT in the observational record. To date, attempts at finding observational evidence for the link between solar activity/CR and climate have relied on simple linear cross correlation or spectral coherence analysis (6, 13–17). Although suggestive, it is well known that

## Significance

Here we use newly available methods to examine the dynamical association between cosmic rays (CR) and global temperature (GT) in the 20th-century observational record. We find no measurable evidence of a causal effect linking CR to the overall 20th-century warming trend; however, on short interannual timescales, we find a significant, although modest, causal effect of CR on short-term, year-to-year variability in GT. Thus, although CR clearly do not contribute measurably to the 20th-century global warming trend, they do appear as a nontraditional forcing in the climate system on short interannual timescales, providing another interesting piece of the puzzle in our understanding of factors influencing climate variability.

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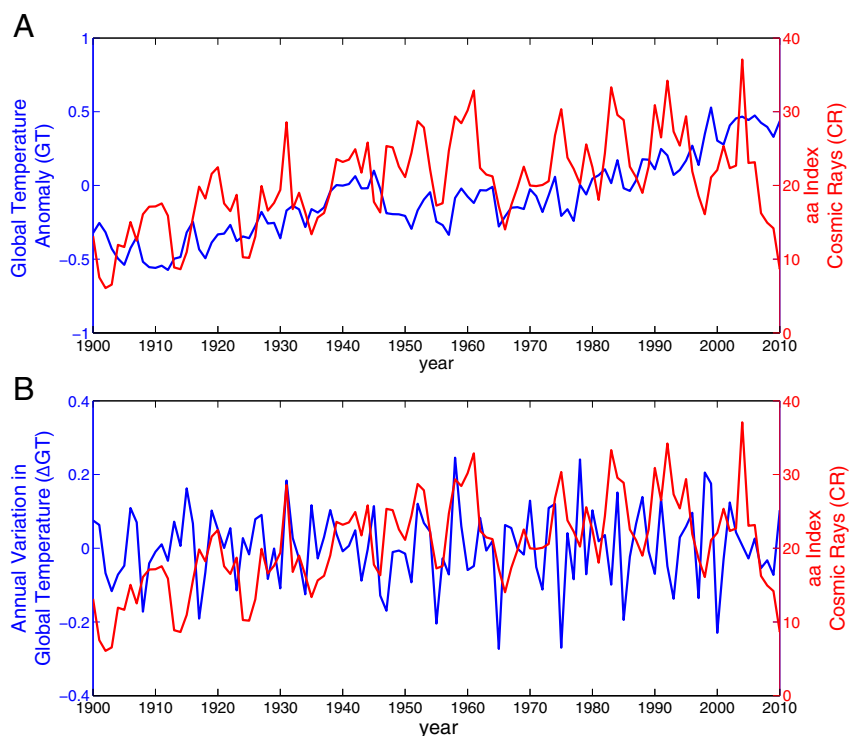
such statistical analyses cannot actually establish causation and, indeed, can be highly misleading in moderate to weakly coupled nonlinear dynamical systems, where “mirage correlations” (spurious correlations that come and go and even change sign) are common (18). Indeed, the singular case in which correlation is valid in nonlinear dynamical systems would require strong coupling (so-called synchrony) between the solar-mediated CR forcing and the climate system, which is unlikely on decadal timescales because of embedded nonlinearities in the climate system. Thus, to test for causal linkage between CR and GT, we apply a recently developed method, convergent cross mapping (CCM) (18), which is based on empirical dynamic modeling (18–20), as described here. This method is specifically designed to measure causality in nonlinear dynamical systems.

For this analysis, we use the aa index (21) as the CR proxy. This index is a well-documented proxy that characterizes magnetic activity resulting from the interaction between solar wind and Earth’s magnetic field (stronger solar wind → stronger magnetic disturbances → higher aa index). The GT record we used is the HadCRUT3 set of the United Kingdom’s Met Office. There is increasing uncertainty before 1900 in both data series, so we confine our analysis to the post-1900 period and use yearly averages. The chosen interval represents a compromise between noise in the data and sample size. Both time series exhibit a positive trend; however, the GT warming trend is more distinct and dominates the much smaller superimposed interannual fluctuations (Fig. 1A). This is in contrast to the CR record, in which large interannual variation dominates the 20th-century signal.

CCM is a new methodological approach that can help distinguish causality from spurious correlation in time series from dynamical systems (18). The technique is based on the idea that causation can be established if states of the causal variable can be recovered from time series of the affected variable. For example, if past sea surface temperatures can be estimated from

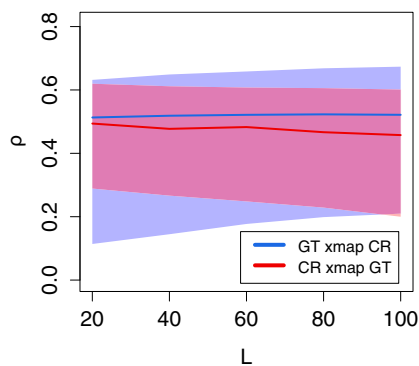
time series of sardine abundance, temperature had a measurable and recoverable influence on the population dynamics of sardines (18). The idea is based on empirical dynamics (18–20) and a theorem proven by Takens (22), which states that the essential information of a multidimensional dynamical system is retained in the time series of any single variable of that system. Thus, CCM uses Takens’ theorem to detect whether two variables belong to the same dynamical system. Effectively, if variable  $X$  is influencing  $Y$ , then causality is established if states of the causal variable  $X$  can be recovered from the time series history of  $Y$ . Simply put, CCM measures the extent to which the historical record of the affected variable  $Y$  (or its proxies) reliably estimates states of a causal variable  $X$  (or its proxies), which is quantified by calculating the correlation coefficient  $\rho$  between predicted and observed  $X$ . If the skill of cross mapping increases with the length of the time series, a direct or indirect causal effect of  $X$  on  $Y$  can be inferred. The relative level to which predictive skill converges (“CCM skill” hereafter) can be viewed as an estimator of the strength of the causal link. Convergence occurs with additional data as the underlying attractor manifold becomes denser and the nearest neighbors get closer. The essential mechanics of CCM are detailed in Sugihara and colleagues (18) and are summarized in three 1-min animations (Movies S1–S3).

CCM can identify bidirectional causality when variables are mutually coupled [the primary case covered by Takens (22)], as well as unidirectional causality when  $X$  influences  $Y$  but  $Y$  has no effect on  $X$ , as occurs when  $X$  is an external forcing variable. As explained in Sugihara and colleagues (18), CCM applies in dynamical systems, in contrast to Granger causality (23) framework (SI Appendix), which is aimed at purely stochastic systems that exhibit linear “separability” (independence between variables), in which case, Takens’ theorem does not apply. Specifically, CCM addresses cases not covered by Granger involving interdependent (nonlinear) dynamical systems (i.e., cases in which



**Fig. 1.** (A) Annual values for the aa index (CR proxy) and normalized GT, and (B) annual variations (first-differences) in GT ( $\Delta$ GT) and CR. Despite a correlation between the CR and raw GT time series ( $\rho = 0.38$ ), there is no measurable dynamic causality on the century-long timescale (Fig. 4). However, on the annual timescale, even though CR and  $\Delta$ GT are not correlated ( $\rho = 0.02$ ), evidence suggests they are dynamically coupled (Fig. 3).





**Fig. 4.** CCM analysis between CR and raw GT time series with the secular warming trend shows no convergence and no significance with surrogates generated as in Fig. 3. Thus, although CR is statistically correlated with GT ( $\rho = 0.38$ ), it shows no measurable causal effect on the 20th-century warming trend.

lacking any mechanism for CR to affect temperature. As expected (*SI Appendix, Fig. S6*), there is no significant cross mapping between the historical CR time series and  $\Delta$ GT from the model. As a further check, in *SI Appendix, Fig. S7*, cross mapping results are shown as observed versus predicted along the CR time series (the overall correlation coefficient is 0.20 in accordance with the blue line in Fig. 3). In addition, in *SI Appendix, Fig. S8*, cross mapping is done with sixfold cross validation, where the cross map period is held out of sample from the libraries used to predict the out-of-sample period. We observe that in five of six subperiods, the correlation coefficient between actual and predicted values is positive, as one would expect when CR causes  $\Delta$ GT. Given the small sample sizes involved, as well as the fact that the effect of CR on  $\Delta$ GT is weak to moderate, this result provides additional support for causality between CR and  $\Delta$ GT.

As might be expected from the S-map analysis, there is no detectable convergence with the raw GT data containing the 20th-century warming trend (Fig. 4). The nonconvergent cross map signal is consistent with a statistical association that is noncausal in terms of dynamic coupling (18). Indeed, the cross map estimates contain less information than is contained in the linear trend of GT

( $\rho = 0.8$ ), reflecting little beyond the incidental cross-correlation between CR and GT ( $\rho = 0.38$ ). Lack of convergence combined with a failure to manifest significance beyond the surrogates demonstrates that CR has no discernable causal effect on the overall warming pattern for the 20th century. The analysis shows that the dominant warming signal on this century-long timescale is not a measurable consequence of dynamic forcing by CR.

For completeness, a traditional Granger causality (23) analysis was implemented. Because the S-map test demonstrated that the CR time series is from a nonlinear dynamical system and not a purely stochastic one, Granger's test should not apply (18). Granger causality requires separability (dynamic independence of system parts), and is therefore not defined for interdependent dynamic systems. Thus, it is not surprising that the Granger test fails to detect any meaningful association (in fact, the nonsensical case for temperature affecting CR is slightly stronger by Granger's test; *SI Appendix, SI Text*).

## Summary

Our results suggest weak to moderate coupling between CR and year-to-year changes of GT. They resonate with the physical and chemical evidence emerging from laboratory studies suggesting a theoretical dynamic link between galactic CR and GT. However, we find that the realized effect is modest at best, and only recoverable when the secular trend in GT is removed (by first-differencing). Thus, it is important to stress that they do not suggest that CR influences can explain global warming and should not be misinterpreted as being in conflict with the IPCC (25). Indeed, the opposite is true: we show specifically that CR cannot explain secular warming, a trend that the consensus attributes to anthropogenic forcing. Nonetheless, the results verify the presence of a nontraditional forcing in the climate system, an effect that represents another interesting piece of the puzzle in our understanding of factors influencing climate variability.

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- Ney ER (1959) Cosmic radiation and weather. *Nature* 183:451–452.
- Duplissy J, et al. (2010) Results from the CERN pilot CLOUD experiment. *Atmos Chem Phys* 10:1635–1647.
- Kirkby J, et al. (2011) Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation. *Nature* 476(7361):429–433.
- Svensmark H, Pedersen JOP, Marsh ND, Enghoff MB, Uggerhoj UI (2007) Experimental evidence for the role of ions in particle nucleation under atmospheric conditions. *Proc R Soc A* 463:385–396.
- Enghoff MB, Pedersen JOP, Uggerhoj UI, Paling SM, Svensmark H (2011) Aerosol nucleation induced by high energy particle beam. *Geophys Res Lett* 38:L09805.
- Marsh ND, Svensmark H (2000) Low cloud properties influenced by cosmic rays. *Phys Rev Lett* 85(23):5004–5007.
- Harrison RG, Ambaum MHP, Lockwood M (2011) Cloud bases height and cosmic rays. *Proc R Soc Lond A* 467:2777–2791.
- Rawal A, Tripathi SN, Michael M, Srivastava AK, Harrison RG (2013) Quantifying the importance of galactic cosmic rays in cloud microphysical processes. *J Atmos Sol Terr Phys* 102:243–251.
- Svensmark H, Enghoff MB, Pedersen JOP (2013) Response of cloud condensation nuclei (> 50 nm) to changes in ion-nucleation. *Phys Lett A* 377:2343–2347.
- Zhang R, Khalizov A, Wang L, Hu M, Xu W (2012) Nucleation and growth of nanoparticles in the atmosphere. *Chem Rev* 112(3):1957–2011.
- Yu F (2005) Quasi-unary homogeneous nucleation of H<sub>2</sub>SO<sub>4</sub>-H<sub>2</sub>O. *J Chem Phys* 122(7):074501.
- Foukal P, Fröhlich C, Spruit H, Wigley TML (2006) Variations in solar luminosity and their effect on the Earth's climate. *Nature* 443(7108):161–166.
- Neff U, et al. (2001) Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. *Nature* 411(6835):290–293.
- Bond G, et al. (2001) Persistent solar influence on North Atlantic climate during the Holocene. *Science* 294(5549):2130–2136.
- Svensmark H (1998) Influence of cosmic rays on Earth's climate. *Phys Rev Lett* 81:5027–5030.
- Usoskin IG, Marsh N, Kovaltsov GA, Mursula K, Gladysheva OG (2004) Latitudinal dependence of low cloud amount on cosmic ray induced ionization. *Geophys Res Lett* 31(16):L16109.
- Shaviv N (2003) The spiral structure of the Milky Way, cosmic rays, and ice age epochs on Earth. *New Astron* 8:39–77.
- Sugihara G, et al. (2012) Detecting causality in complex ecosystems. *Science* 338(6106):496–500.
- Sugihara G, May RM (1990) Nonlinear forecasting as a way of distinguishing chaos from measurement error in time series. *Nature* 344(6268):734–741.
- Sugihara G (1994) Nonlinear forecasting for the classification of natural time series. *Philos Trans R Soc Lond A* 348:477–495.
- Nayaud PN (1972) The aa indices: A 100-year series characterizing magnetic activity. *J Geophys Res* 17:6870–6874.
- Takens F (1981) Detecting strange attractors in turbulence. *Dynamical Systems and Turbulence*, eds Rand DA, Young L-S (Springer, New York), pp 366–381.
- Granger CWJ (1969) Investigating causal relations by econometric models and cross-spectral analysis. *Econometrica* 37:424–438.
- Ebisuzaki W (1997) A method to estimate the statistical significance of a correlation when the data are serially correlated. *J Clim* 10:2147–2158.
- Solomon S, et al. (2007) *Climate Change 2007: The Physical Science Basis*. Available at [www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4\\_wg1\\_full\\_report.pdf](http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4_wg1_full_report.pdf).