The Autocorrelation Function and Human Influences on Climate

T. M. L. Wigley *et al.* (*1*) compare the autocorrelation function of the observed hemispheric temperature records to the autocorrelation function of similar records of control climate model simulations. When the models are unforced, the differences between the autocorrelation functions are significant, probably as a result of the fact that unforced models do not produce the long-term trends evident in the observed records. The differences between the autocorrelation functions diminish when natural (solar) and anthropogenic influences are removed from the observed data. Wigley *et al.* correctly acknowledge that their interpretations assume that the control model runs simulate the unforced behavior of the climate system realistically. They test this assumption by again comparing autocorrelation functions of model and adjusted-observed data. On the basis of these comparisons, Wigley *et al.* conclude that there is a human influence on climate in the last century.

This result is impressive, and there may indeed be a human influence on climate. However, the use of the autocorrelation function as a tool for such comparisons presents a problem. Climate models, whether forced or unforced, constitute dynamical systems. If these models faithfully represent the dynamics of the climate system, then a comparison between an observation and a model simulation should address whether or not these two results have the same dynamical foundation.

Let us assume that $x(t)$ is a realistic model simulation of the hemispheric mean temperature record and $y(t)$ is a reliable measurement of hemispheric mean temperature. Under these circumstances, both $x(t)$ and $y(t)$ can be considered as faithful dynamical representations of the climate system. Accordingly, their autocorrelation functions should be similar. Now let us consider $x(t)$ with its autocorrelation function $r(k)$ and Fourier transform $F(f)$, where k is the temporal lag and f is the frequency. According to the Weiner-Khintchine theorem (*2*), the spectral density function $S(f) = 1/T\,|F(f)|^2$ is the Fourier transform of the autocorrelation function $r(k)$. The Fourier transform has a complex amplitude at each frequency. If we multiply each complex amplitude by $e^{i\phi}$, where ϕ is a random variable as it occurs in the interval $[0,2\pi]$ (randomization of phases) and then take the inverse Fourier transform, we will produce a new time series $x'(t)$. This time series exhibits the same Fourier transform (and through the Weiner-Khintchine theorem, the same autocorrelation function) as $x(t)$, but it is devoid of information related to the dynamics that produced $x(t)$. In other words, $x'(t)$ represents a surrogate stochastic process exhibiting not only similar mean and variance, but a similar autocorrelation function as the deterministic process $x(t)$ (*3*). Similarly, we can produce a stochastic time series $y'(t)$ that would be a surrogate to $y(t)$.

Thus, because two time series have similar autocorrelation functions, it does not necessarily follow that the two time series represent the same dynamics. Accordingly, linking $x(t)$ to $y(t)$ by simply comparing their autocorrelation functions does not provide a rigorous proof that one is a realistic representation of the other. Otherwise stated, if we are concerned about whether the models realistically represent the climate system, then any statistical testing where the null hypothesis involves the autocorrelation function is meaningless. The heart of the problem lies in the fact that the variability of the climate system depends on the unique configuration of the phases caused by both internal and external forcings and their nonlinear interactions. When this uniqueness is destroyed, what remains is a linear process. As such, results from the analysis presented in the report by Wigley *et al.* (*1*) are unsubstantiated.

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Submitted 12 January 1999; accepted 12 May 1999

Response: The central point of the comment by Tsonis and Elsner, that the autocorrelation function does not uniquely determine the dynamics of a nonlinear series, is unquestionably correct (and well known). This point, however, does not invalidate the use of the autocorrelation function in a hypothesis-testing context.

In any test of a hypothesis, it is necessary to select a test statistic with a distribution that can be characterized under some null hypothesis. If the observed value of the statistic lies outside a specified acceptance region for the null distribution (determined by the chosen level of significance), then we conclude that the data are inconsistent with the null hypothesis. If the test statistic lies within the acceptance region, then the null hypothesis cannot be rejected, but this does not mean that we have proved the null hypothesis to be correct.

In our study (*1*), we first compared the autocorrelation functions of observed hemispheric-mean temperature data with those for unforced data obtained from two different climate models. We found substantial (statistically significant) differences. We concluded, therefore, that the null hypothesis of no forcing could not be correct. This conclusion is not affected by the comment of Tsonis and Elsner. Although similar autocorrelation functions do not necessarily imply similar dynamics (their main point), different autocorrelation functions, in stationary systems, do imply different dynamics.

We extended this analysis by adjusting the observations for various kinds of external forcing. When solar forcing effects alone were considered, with the use of a realistic value for the climate sensitivity, we found that the autocorrelation functions of the adjusted observed data (that is, of the residuals after removing the solar effect) again differed substantially from the model data with no external forcing. We therefore concluded that solar forcing alone could not account for the autocorrelation character of the raw observed data. This result, as before, is not affected by the comment of Tsonis and Elsner.

In other cases where we subtracted combinations of natural and anthropogenic forcing effects from the observed data, the autocorrelation functions of the residuals were similar to those for the unforced model data. The comment by Tsonis and Elsner notes that we cannot conclude from this that the two series have the same dynamics. We agree. Close similarity of the autocorrelation functions does not prove that the residuals that remain after external forcing effects have been removed from the observations have the same dynamics as the unforced climate model data. In these cases, however, all we are claiming is consistency between the observations and our hypothesized decomposition of the data into the sum of the effects of various external forcing factors and internally generated (unforced) variability. Demonstrating such consistency is important, because lack of consistency might cause one to question the external forcing hypothesis.

Our autocorrelation analysis, like any scientific study in a complex field, was never meant to be considered in isolation. Our results are another piece in the climate-change jigsaw puzzle, demonstrating a form of consistency that is similar in principle to the consistency between modeled and observed global-mean temperature changes over the past 100 years (*2*). In neither case does consistency *prove* a cause and effect relationship between anthropogenic forcing and observed climate change. To address cause and effect issues more directly, the favored method is some form of "fingerprint" analysis based on a comparison of observed and modeled patterns of change and their time evolution (*3*). Recent studies in this area (*4*) support our conclusion that both solar and anthropogenic forcing effects are required to explain the past record.

We agree with Tsonis and Elsner that in highly nonlinear series, the autocorrelation function is less likely to be a significant tool. Indeed, they specifically refer to the possibility of nonlinear interactions between internal variability and external forcings. At the level of spatial and temporal aggregation that we consider, however, we believe that there is strong evidence that linear systems do provide adequate models (*5*). Linear additivity is also central to more fundamental aspects of climate such as radiative forcing (*6*).

In conclusion, the comment by Tsonis and Elsner makes a point that is technically correct, but does not invalidate any of the conclusions of our report.

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19 February 1999; revised 29 June 1999; accepted 6 July 1999