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Long-run changes in radiative forcing and surface temperature: The effect of human activity over the last five centuries

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ABSTRACT

We test two hypotheses that are derived from the anthropogenic theory of climate change. The first postulates that a growing population and increasing economic activity increase anthropogenic emissions of radiatively active gases relative to natural sources and sinks, and this alters global biogeochemical cycles in a way that increases the persistence of radiative forcing and temperature. The second postulates that the increase in the persistence of radiative forcing transmits a stochastic trend to the time series for temperature. Results indicate that the persistence of radiative forcing and temperature changes from $I(0)$ to $I(1)$ during the last 500 years and that the $I(1)$ fingerprint in radiative forcing can be detected in a statistically measureable fashion in surface temperature. As such, our results are consistent with the physical mechanisms that underlie the theory of anthropogenic climate change.

Introduction

Two foci for statistical analyses of global climate change are the times series properties of radiative forcing and global temperature and whether natural and/or anthropogenic components of radiative forcing are related to surface temperature in a statistically meaningful way. These foci evolve from concerns that ignoring the properties of the time series could lead to ambiguous results. Specifically, if the time series for radiative forcing and/or surface temperature contain a stochastic trend, statistical methods that assume the data are stationary, such as ordinary least squares (OLS), could generate spurious regression results. That is, the standard diagnostic statistics that are used to evaluate results generated by OLS will indicate a statistically meaningful relation among non-stationary time series in about 85 percent of the cases even when the data generating processes are unrelated (Hendry and Juselius, 2000).

Efforts to understand the time series properties of climate data start with Bloomfield and Nychka (1992) and Woodward and Gray (1993, 1995). These studies find that global temperature is non-stationary but are split regarding the data generating process (DGP), a deterministic or stochastic trend. Two studies (Bloomfield and Nychka, 1992; Woodward and Gray,

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1993) find that the temperature time series contains a deterministic trend while Woodward and Gray (1995) find evidence for a stochastic trend. Recent studies such as Stern and Kaufmann (2000) and Kaufmann et al. (2013) report additional evidence for a stochastic trend in temperature. Overall, the literature contains considerable evidence that the temperature time series is $I(1)$. Conversely, many studies find that the time series for the radiative forcing of greenhouse gases (e.g. carbon dioxide, methane, nitrous oxide, CFCs), are $I(2)$, while the radiative forcing of sulfur aerosols and solar insolation generally are $I(1)$ (Stern and Kaufmann, 2000, 1999; Kaufmann et al., 2006a). Given that the radiative forcing of greenhouses gases (and mainly of carbon dioxide) are integrated one order higher than that of temperature, these differences would seem to preclude a relation between temperature and aggregate radiative forcing.

Analysts attempt to reconcile this seeming contradiction in several ways. One approach argues that univariate tests, especially the Augmented Dickey–Fuller (ADF) statistic, do not generate reliable results for the temperature time series. Visual examination of the time series for surface temperature during the instrumental record (1850-present) indicates that values vary greatly from year to year. This variability suggests that if the anthropogenic components of radiative forcing affect climate by altering surface temperature, this signal may be obfuscated by natural variability, which implies that the temperature time series has a low signal to noise ratio (Stern and Kaufmann, 2000). When applied to such time series, the ADF statistic (and other unit root tests) rejects the null hypothesis too frequently when the true DGP is a random walk with noise and the noise is large compared to the signal (Enders, 1995; Hamilton, 1994). In a finite sample, reducing the signal to noise ratio increases the probability that the test will indicate a trend stationary variable, a type I error (Enders, 1995). This conclusion is reinforced by Monte Carlo simulations (Schwert, 1989; Phillips and Perron, 1988; Kim and Schmidt, 1990). Conversely, these effects may be offset by the presence of deterministic cycles, which may bias inferences in favor of failing to reject the null hypothesis of a unit root (Robinson, 1994).

A second approach exploits the notion of cointegration (using univariate or multivariate framework) to examine the time series properties of temperature and radiative forcing. Implementing a univariate approach, Kaufmann et al. (2006a, 2011) find that the radiative forcing of greenhouse gases, anthropogenic sulfur emissions, and solar insolation cointegrate with temperature over a variety of sample periods as indicated by ADF tests conducted on the residuals of the cointegrating regression.[1] If a low signal to noise ratio obfuscates the stochastic trend in the temperature time series, multivariate test statistics can be used to evaluate whether the time series for temperature and radiative forcing have the same order of integration and if they do, whether they share the same stochastic trend (i.e. do they cointegrate). The hypothesis that surface temperature and radiative forcing share the same stochastic trend is based on physical principles; models that simulate climate for the planet as a whole (i.e. zero dimensional climate models) can be rewritten as cointegration/error-correction models (Kaufmann et al., 2013). Consistent with this theoretical underpinning, several empirical studies indicate that the time series for temperature and radiative forcing are $I(1)$ and share the same stochastic trend. For example, Stern and Kaufmann (2000) employ a structural time series approach and find that the radiative forcing of greenhouse gases, solar radiation, and anthropogenic sulfur emissions can account for stochastic trends in Northern and Southern Hemisphere temperatures. Using the Johansen (1995) cointegration approach, Kaufmann and Stern (2002) find that temperature cointegrates with radiative forcing and that this cointegrating relation must include the radiative forcing of greenhouse gases, anthropogenic sulfur emissions, and solar insolation.

A third approach argues that temperature is neither stationary nor integrated order one, but rather is trend stationary with a break. Gay et al. (2009) find that they cannot reject the null hypothesis that global temperature and temperatures in the Northern and Southern Hemispheres are trend stationary with a one time permanent shock in 1977, 1985, and 1911, respectively. In response, Kaufmann et al. (2010, 2013) argues that (1) there is no physical basis for radiative forcing to evolve in a deterministic manner, (2) the time series for radiative forcing cannot be modeled empirically as trend stationary with a one-time shock, (3) cointegration and error-correction models generate a more accurate in-sample forecast than the trend stationary model, and (4) Monte Carlo simulations of the cointegration/error-correction model can generate time series for temperature that appear to be trend-stationary-with-a-break when analyzed with the statistical methodology used by Gay et al. (2009).

We build on these results by compiling time series for temperature, greenhouse gas concentrations (CO_2, CH_4, N_2O, CFC-12, CFC-11), anthropogenic sulfur emissions, the Southern Oscillation index, volcanic activity, and solar insolation over a five hundred year period (1500–2011) and testing two hypotheses that are implied by the anthropogenic theory of climate change. According to this theory, forcings that are associated with human activity (e.g. increases in the atmospheric concentration of CO_2 due to anthropogenic emissions) have little effect on climate prior to the Industrial Revolution because human actions have little effect on global biogeochemical cycles during this period. After the Industrial Revolution, changes in the types and magnitude of human activities increase human impacts on global biogeochemical cycles. These impacts lead to significant changes in radiative forcing and ultimately, global temperature. This general description leads to two hypotheses about how changes associated with the Industrial Revolution can be used to test indirectly the anthropogenic theory of climate change:

Hypothesis I. If a growing population and increasing economic activity increase anthropogenic emissions of radiatively active gases relative to natural sources and sinks, this will alter global biogeochemical cycles. Such alterations will change

[1] A high noise to signal ratio could cause these results to 'over-reject' the null of no-cointegration.