Robust Granger Causality Testing of the Effect of Natural and Anthropogenic Radiative Forcings on Global Temperature

David I. Stern
Crawford School of Public Policy, Australian National University, Canberra ACT 0200, Australia
david.stern@anu.edu.au

Robert K. Kaufmann
Department of Earth and Environment, Boston University, Boston MA 02215, USA
kaufmann@bu.edu

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Despite a strengthening consensus that the increase in anthropogenic emissions of greenhouse gases is partially responsible for the observed increase in global temperature since the mid-20th century, scientific debate continues on several issues, including the relative size of individual causes of climate change such as sulphate aerosols (Kaufmann *et al*., 2011), the El Nino-Southern Oscillation (Compo and Sardeshmukh, 2010; Tung and Zhou, in press), black carbon (Bond *et al*., in press), the existence of climate feedbacks on the global carbon cycle (Piao *et al*., 2008; Barichivich *et al.,* 2012), and whether increases in carbon dioxide precede or follow global warming (Shakun *et al*., 2012; Parennin *et al*., 2013). Here, we test for causality between radiative forcing and temperature using multivariate time series models and Granger causality tests that are robust to the non-stationary (trending) nature of global climate data. We find that both natural and anthropogenic forcings cause temperature change and also that temperature causes greenhouse gas concentrations. Additionally, though the effects of greenhouse gases and volcanic forcing are robust across model specifications, we cannot detect any effect of black carbon on temperature, the effect of changes in solar irradiance is weak, and the effect of anthropogenic sulphate aerosols may be only around half that usually attributed to them (Boucher and Pham, 2002).

One approach to detecting and attributing climate change involves estimating time series models of the relation between temperature and relevant forcing variables (e.g. Stone and Allen, 2005; Stern, 2006; Lean and Rind, 2008; Beenstock *et al.*, 2012; Canty *et al.*, 2012). The validity of these models depends critically on the time series properties of the variables and the model residuals (Stern and Kaufmann, 2000). Specifically, the time series for many forcings are non-stationary, and may be stochastically trending (Stern and Kaufmann, 2000) – only the changes in the variable are stationary - which invalidates the naive application of classical static regression analysis. However, it is very hard to identify the actual data generating process, and therefore the statistical properties of the time series, because available tests have low statistical power to discriminate among alternatives and the temperature series, in particular, are noisy due to internal variability (Stern and Kaufmann, 2000).

Alternatively, robust Granger causality tests that do not depend on the statistical properties of the time series (Toda and Yamamoto, 1995) may offer a more reliable approach to attributing climate change to specific forcings. A time series variable x (e.g. radiative forcing) is said to Granger cause variable y (e.g. surface temperature) if past values of x help predict the current level of y given all other relevant information. These hypotheses can be tested by estimating a multivariate time series model, known as a vector autoregression (VAR), for x, y, and other relevant variables. The VAR models the current values of each variable as a linear function of their own past values and those of the other variables. Then we test the hypothesis that x does not cause y by evaluating restrictions that exclude the past values of x from the equation for y and *vice versa*.

To identify causal relations between radiative forcing and temperature and explore uncertainty about the effects, we compile annual global time series data for temperature and an expanded set of radiative forcings from 1850 to 2011, create several scenarios for the relative size of uncertain forcings, and test for Granger causality between the radiative forcing and temperature series using Toda and Yamamoto's (1995) robust Granger causality test.

The scenarios for the relative size of the forcings allows us to explore the considerable uncertainty regarding the effects of black carbon and anthropogenic sulphate emissions (Forster *et al.*, 2007). Bond *et al.*, (in press) find that the radiative forcing due to black carbon is likely to be much greater than previously estimated. However, this new estimate has a wide confidence interval that also includes zero. We investigate this uncertainty by evaluating scenarios for a range of values for the radiative forcing of black carbon and sulphate aerosols. The standard scenario (indicated as BC=1, S=1) assumes that the radiative forcing of black carbon and anthropogenic sulphate aerosols in 1990 is 0.31 Wm^{-2} (Meinshausen *et al*., 2011) and -1.42 Wm^{-2} (Boucher and Pham, 2002), respectively.

Based on these values, anthropogenic forcing (greenhouse gases, sulphur emissions, and black carbon) is low until 1970 after which it increases sharply (Figure 1a). Natural forcings are dominated by large volcanic eruptions (Figure 1b). In the last decade, total anthropogenic and natural forcing is fairly constant due to a decline in natural forcing and a slight slowing in the growth of the anthropogenic forcing. This might explain the relative hiatus in global temperature increase in this period (Kaufmann *et al*., 2011). Similarly, both atmospheric temperature and ocean heat content show an increase starting around 1970 and a slowing during the last decade (Figure 2). Alternative scenarios (BC = 0, S = 1 and BC = 3, S = 1) assume that black carbon either makes no contribution to global warming or has three times the standard effect, or (BC = 0, S = 0.5) assumes that black carbon has no effect and anthropogenic sulphate aerosols have only half their default cooling effect. The curve for this final scenario (Figure 1a) is smoother than the others and almost monotonic and appears visually to fit the history of global temperature (Figure 2) better.

Limited observations mean that we cannot test all forcing variables separately. Therefore, some aggregation is needed. To allow for uncertainties in the strength of forcings and for the fact that greenhouse gases might be endogenous to temperature while other forcings are exogenous, we test three levels of aggregation (Tables 1 and 2). For Models I and II, total, anthropogenic, and natural radiative forcing (RFTOT, RFANTH, and RFNAT) are computed by summing their components and these aggregates are used in the regression models. We also test the total effect of anthropogenic and natural forcing in the most disaggregated model, Model III, by imposing joint restrictions that exclude all of the anthropogenic or all of the natural forcings.

We run all tests on the full sample (1850-2011) and a 1958-2011 sample. 1958 marks the start of on-going direct measurements of atmospheric CO_2 that are probably more reliable than the earlier data derived from ice cores. However, this sample results in a very short time series, which may weaken the reliability of results. For the 1958-2011 sample, we also test models that include ocean heat content. The oceans store most of the increase in heat due to increased radiative forcing, therefore models that omit ocean heat content are misspecified

(Stern, 2006) and bias statistical estimates of the climate sensitivity (Stern, 2006; Mascioli *et al.*, 2012).

Model I, which aggregates all forcings, shows unambiguously that radiative forcing causes temperature but not *vice versa* (Table 1). Model II, which disaggregates total forcings into anthropogenic and natural forcings, highlights the uncertainty about the strength of forcings. Contrary to some recent studies (Pasini *et al.*, 2012; Attanasio, 2012), natural forcing causes temperature in all scenarios. Conversely, anthropogenic forcing causes temperature (at the 5% level) only when we assume that the black carbon forcing is zero and the sulphur forcing is weak (BC = 0, S = 0.5). A couple of other results also suggest that anthropogenic forcings cause temperature, but only at the 10% significance level. For most of the Model II scenarios, there is little evidence that temperature Granger causes anthropogenic forcing.

Model III shows the importance of disaggregating the forcings. Greenhouse gases and anthropogenic sulphate aerosol cause temperature in all but one of the samples each but we cannot find a causal effect for black carbon, which is consistent with Kaufmann *et al.* (2011). Volcanic aerosols (RFVOL) are highly significant in all samples while solar irradiance (RFSOL) is much less significant or totally insignificant depending on the sample.

Model III also shows that temperature causes greenhouse gases. We investigate this result further by disaggregating greenhouse gases into the temperature sensitive carbon dioxide and methane and the other non-temperature sensitive gases – nitrous oxide and CFC's. Results (not reported) indicate that temperature Granger causes carbon dioxide and methane, but temperature has no causal effect on the other non-temperature sensitive greenhouse gases. The two-way causal relation between temperature and carbon dioxide is consistent with the recent findings of a synchronous change of atmospheric CO_2 and Antarctic temperature since the last glacial maximum (Parrenin *et al.*, 2013; Kaufmann and Juselius, in press).

The sum of the coefficients associated with lagged temperature in the vector autoregression model is positive, which suggests that a warming climate changes carbon flows to and from the atmosphere such that on net, a warming climate increases the flow of carbon to the atmosphere. This summation is not always a reliable indicator of either the short- or long-run effect (Wilde, 2012), but this result is consistent with findings that temperature has a positive short-run feedback effect on the atmospheric concentration of carbon dioxide (Kaufmann *et al.*, 2006) and that the rate of increase of atmospheric CO_2 is positively correlated with global temperature and is higher during El Nino events and lower following major volcanic eruptions such as Mount Pinatubo (Keeling *et al*., 2005).

As a robustness test, we repeat all tests using the GISS3 temperature data (Table 2). The results of the causality tests are similar. The main difference is that in many cases, evidence for the causal effects of greenhouse gases in Model III and anthropogenic forcing in Model II is stronger for the HADCRUT4 data. The results are also similar across the two sample periods and for models with and without ocean heat content.

The results reported here are more robust than those reported by other recent efforts to use Granger causality to attribute the causes of climate change (Attanasio, 2012; Bilancia and Vitale, 2012, Attanasio *et al*., 2012; Kodra *et al*., 2011). Kaufmann and Stern (1997) pioneered the use of the Granger causality technique, developed in macroeconomics, to attribute changes in the instrumental temperature record to anthropogenic activities and/or natural causes. Their study took an indirect approach, testing whether the radiative forcing of greenhouse gases and/or aerosols could explain the causal effect of Southern Hemisphere on Northern Hemisphere temperatures they found using a bi-variate model.

This indirect approach was criticized (Triacca, 2001), and, so, recent studies take a direct approach by testing for causality between individual forcings and temperature (Triacca, 2005; Attanasio, 2012; Bilancia and Vitale, 2012, Attanasio *et al*., 2012; Kodra *et al*., 2011; Pasini *et al*., 2012). Nevertheless, these studies are problematic because they test the effect of potential causes one at a time and, in many cases, use statistical methodologies that are not appropriate for the non-stationary (trending) nature of the data.

In a test of the Granger causality between x and y, if a third variable, z, drives both x and y, x might still appear to cause y though there is no causal mechanism that directly links the variables. As a result, omitted variable bias (i.e. the bias in regression estimates due to omitting z from the analysis of x and y) can affect conclusions about causality (Lütkepohl, 1982). Indeed, Kaufmann and Stern (1997) argue that their finding of causality from Southern Hemisphere to Northern Hemisphere temperatures is spurious, caused by the omission of greenhouse gases and anthropogenic sulphur emissions from that model.

Similarly, conclusions about causality generated by previous models may be spurious because the time series properties of the data affect the critical values that should be used to evaluate statistical tests of Granger causality. Several studies suggest that many of the time series for trace gases are stochastically trending – only differencing can render them stationary - as opposed to stationary around a constant mean, a deterministic trend, or a deterministic trend with a one-time change (Stern and Kaufmann, 2000; Kaufmann *et al.,* 2013). Testing for causality among stochastically trending time series with critical values from standard distributions overstates the likelihood of causality if the time series are not cointegrated (Toda and Phillips, 1993). To avoid this source of confusion, some analysts (e.g. Bilancia and Vitale, 2012; Kodra *et al*., 2011) remove the stochastic trend by differencing the data. But differencing is not appropriate because it potentially eliminates long-run effects and so can only provide information on short-run effects.

Using statistical models and methods that alleviate issues associated with omitted variable bias and the stochastically trending time series, the results reported here show that properly specified tests of Ganger causality validate the consensus that human activity is partially responsible for the observed rise in global temperature and that this rise in temperature also has an effect on the global carbon cycle. Finally, Granger causality might be able to narrow the range of uncertainty about individual forcings in a way that ultimately improve our ability to forecast futures changes in climate. This hypothesis is speculative and should be investigated using Monte Carlo simulation methods.

Methods

Data Sources and Calculations of Radiative Forcing

Temperature: We use two global land-sea temperature series - HADCRUT4 (Morice *et al*., 2012) and GISS v3 GLOBAL Land-Ocean Temperature Index (Hansen *et al*., 2010). GISS data is only available from 1880 while HADCRUT4 is available from 1850.

Ocean heat content: We obtain data from:

http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/basin_data.html

We use the 0-700m layer series, as only this data is available with unsmoothed annual observations. Data is available from 1955 to 2011. See Levitus et al. (2012) for more details.

Radiative Forcing: We update to 2011 the sources used in Stern (2006) with the following modifications:

Volcanic sulphate aerosol is based on the optical thickness data from GISS:

http://data.giss.nasa.gov/modelforce/strataer/tau_line.txt

Radiative forcing is -27 times the optical thickness. See Sato *et al*. (1993) for discussion of sources and methods.

Anthropogenic sulphur emissions: We use data from Smith *et al*. (2011) and Klimont *et al*. (2013). Radiative forcing is computed using a modification of the formula in Wigley and Raper (1992) and values from Boucher and Pham (2002) of -0.42Wm^{-2} for direct radiative forcing in 1990 and -1.0Wm^{-2} for indirect forcing in 1990, an indirect forcing of -0.17Wm^{-2} in 1850, and a natural burden of 0.19Tg S and an anthropogenic burden of 0.47 Tg S in 1990. The formula for indirect forcing is: $R_t = -0.13 - 0.87 \ln(1 + h_t S_t / 26) / \ln(1 + h_t S_{1990} / 26)$ where S is annual anthropogenic sulphur emissions in Tg S and h is the stack height term (Wigley and Raper, 1992).

Black and organic carbon: We use the radiative forcing provided in RCP 8.5 (Meinshausen *et al*., 2011). We sum the variables OCI_RF, BCI_RF, BIOMASSAER_RF, and BCSNOW_RF to get the total effect of black and organic carbon.

We considered adjusting the temperature series for the effects of ENSO and other oscillations. However, various series are available which are only weakly correlated, especially in earlier years and various procedures could be used to remove the effects. Some of these approaches (e.g. Compo and Sardeshmukh, 2010; Tung and Zhou, in press) remove much of the variance in the data. However, these oscillations are an endogenous part of the climate system, which might be affected by anthropogenic and natural forcing and, therefore, their effects should not necessarily be removed from the temperature data.

Statistical Methods

To account for the effects of *m* additional variables z_j, the simple bi-variate model used to test for causality between two variables, *x* and *y*, described in the main text, is expanded by estimating the following model:

$$x_t = \alpha_1 + \sum_{i=1}^{p} \Pi^i_{1,1} x_{t-i} + \sum_{i=1}^{p} \Pi^i_{1,2} y_{t-i} + \sum_{j}^{m} \sum_{i=1}^{p} \Pi^i_{1,2+j} z_{j,t-i} + \varepsilon_{1t} \qquad (1)$$

$$y_t = \alpha_2 + \sum_{i=1}^{p} \Pi^i_{2,1} x_{t-i} + \sum_{i=1}^{p} \Pi^i_{2,2} y_{t-i} + \sum_{j=1}^{k} \sum_{i=1}^{p} \Pi^i_{2,2+j} z_{j,t-i} + \varepsilon_{2t} \qquad (2)$$

$$z_{kt} = \alpha_{2+j} + \sum_{i=1}^{p} \Pi^{i}_{2+k,1} x_{t-i} + \sum_{i=1}^{p} \Pi^{i}_{2+k,2} y_{t-i} + \sum_{j=1}^{m}\sum_{i=1}^{p} \Pi^{i}_{2+k,3} z_{jt-i} + \varepsilon_{2+kt}, \forall k = 1,\ldots,k \quad (3)$$

in which t indexes time, p is the number of lags that adequately models the dynamic structure so that the coefficients of further lags of variables are not statistically significant. There are p matrices of regression coefficients Π^{i} , which have dimension $(2+m)\times(2+m)$ and α is *(2+m)* vector of regression coefficients. The error terms ε are white noise though they may be correlated across equations. The null hypothesis $\Pi^{1}_{2,1} = \Pi^{2}_{2,1} = \ldots = \Pi^{p}_{2,1} = 0$ implies that x does not cause y. Rejecting this null indicates that x causes y. Similarly, rejecting $\Pi^{1}_{1,2} = \Pi^{2}_{1,2} = \ldots = \Pi^{p}_{1,2} = 0$ indicates that y causes x.

Failure to reject the null hypothesis that x does not cause y, does not necessarily mean that there is no causal relation between the variables. Instead, a misspecified number of past observations, insufficiently frequent observations (Granger, 1988), too small a sample and hence low statistical power, omitted variables bias (Lütkepohl, 1982), or nonlinearity (Sugihara *et al.*, 2012) can generate a type II error. Nonetheless, a linear VAR should be appropriate for testing for causality because the response of the climate system to forcings appears to be linear and additive on large spatial scales (Stone *et al.*, 2009).

Toda and Yamamoto (1995) modify the standard Granger causality test on the variables in levels so that is robust to the presence of integrated variables and non-cointegration. Their procedure adds additional lags of the variables to the VAR model. One lag is added for each possible degree of integration. So if variables are integrated at most of order one then one additional lag is added and if variables are possibly second order integrated two lags are added. These additional lags are not restricted in the Granger causality test. The test statistic has the classic asymptotically chi-squared distribution with p degrees of freedom. Ignoring deterministic components, the model estimated is:

$$y_t = \alpha + \sum_{i=1}^{p} \Pi_i y_{t-i} + \sum_{i=1}^{d} \Phi_i y_{t-p-i} + \varepsilon_t$$

where y is a vector of n variables, ε is a vector of n white noise error terms, d is the maximal order of integration in the data, and t indexes time. We estimate the model using the seemingly unrelated regressions estimator and imposed the restrictions on the system of equations. We used the Schwert criterion to fix the maximal lag length for the VAR models, which for the 1850-2011 and 1880-2011 samples is 4 lags, and for the 1958-2011 sample is 3 lags. We use the Schwartz Bayesian Information Criterion (SBC) to determine the optimal lag length. To reduce the number of parameters to be estimated we imposed exogeneity restrictions on RFSOX, RFBC, RFVOL, and RFSOL in the disaggregated version of the model.

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Table 1. Granger Causality Tests: HADCRUT4

Sample	1850-2011				1958-2011							
Ocean Heat Content	No				No				Yes			
Alternative Scenarios	BC = 1 S = 1	BC = 0 S = 1	BC = 3 S =1	BC = 0 S = 0.5	BC = 1 S = 1	BC = 0 S = 1	BC = 3 S = 1	BC = 0 S = 0.5	BC = 1 S = 1	BC = 0 S = 1	BC = 3 S = 1	BC = 0 S = 0.5
Model I. HADCRUT4 RFTOT												
RFTOT causes TEMP	0.0021	0.0048	0.0004	0.0008	0.0003	0.0005	0.0001	0.0058	0.0031	0.0055	0.0010	0.0045
TEMP causes RFTOT	0.3475	0.4428	0.2591	0.2836	0.8388	0.8583	0.8166	0.5334	0.5532	0.5968	0.5091	0.6199
Model II. HADCRUT4 RFANTH RFNAT												
RFANTH causes TEMP	0.1925	0.1467	0.6490	0.0297	0.1836	0.3196	0.2294	0.0013	0.0829	0.2649	0.0683	0.0006
RFNAT causes TEMP	0.0292	0.0295	0.0104	0.0238	0.0007	0.0033	0.0002	0.0008	0.0165	0.0217	0.0111	0.0203
TEMP causes RFANTH	0.1211	0.1137	0.0762	0.0931	0.7735	0.6204	0.5015	0.3514	0.3438	0.1824	0.6671	0.9184
Model III. HADCRUT4 RFGHG RFSOX RFBC RFVOL RFSOL												
RFGHG causes TEMP	0.0003				0.0026				0.0221			
RFSOX causes TEMP	0.3187				0.0460				0.0040			
RFBC causes TEMP	0.6884				0.6700				0.4065			
RFGHG, RFSOX, & RFBC cause TEMP	0.0082				0.0090				0.0089			
RFVOL causes TEMP	0.0134				0.0470				0.0071			
RFSOL cause TEMP	0.2380				0.1138				0.1043			
RFVOL & RFSOL cause TEMP	0.0121				0.0678				0.0131			
TEMP causes RFGHG	0.0255				0.0003				0.0016			

Figures are p-values for rejecting the null hypothesis of no causation.

TEMP = Temperature. RF = Radiative forcing, GHG = Greenhouse gases, SOX = Anthropogenic sulphate, BC = Black carbon, VOL = Volcanic aerosol, SOL = Solar irradiance. RFGHG+RFSOX+RFBC=RFANTH (BC=1). RFVOL+RFSOL=RFNAT. RFNAT+RFANTH=RFTOT. Alternative scenarios give coefficients for RFBC and RFSOX in computing RFANTH.

Table 2. Granger Causality Tests: GISS3

Sample	1850-2011				1958-2011							
Ocean Heat Content	No				No				Yes			
Alternative Scenarios	BC = 1 S = 1	BC = 0 S = 1	BC = 3 S =1	BC = 0 S = 0.5	BC = 1 S = 1	BC = 0 S = 1	BC = 3 S = 1	BC = 0 S = 0.5	BC = 1 S = 1	BC = 0 S = 1	BC = 3 S = 1	BC = 0 S = 0.5
Model I. GISS3 RFTOT												
RFTOT causes TEMP	0.0022	0.0043	0.0006	0.0009	0.0000	0.0000	0.0000	0.0000	0.0001	0.0003	0.0000	0.0001
TEMP causes RFTOT	0.5860	0.6972	0.4429	0.4950	0.9141	0.9487	0.8412	0.9287	0.7107	0.7770	0.6200	0.7589
Model II. GISS3 RFANTH RFNAT												
RFANTH causes TEMP	0.3463	0.2631	0.7078	0.0583	0.5856	0.6278	0.5481	0.0087	0.3623	0.4890	0.4205	0.0042
RFNAT causes TEMP	0.0130	0.0179	0.0078	0.0166	0.0000	0.0000	0.0000	0.0000	0.0002	0.0007	0.0000	0.0003
TEMP causes RFANTH	0.2802	0.2648	0.1695	0.2463	0.6876	0.4595	0.6177	0.3674	0.1553	0.0777	0.3305	0.9574
Model III. GISS3 RFGHG RFSOX RFBC RFVOL RFSOL												
RFGHG causes TEMP	0.0004				0.0414				0.0883			
RFSOX causes TEMP	0.1422				0.0663				0.0033			
RFBC causes TEMP	0.3897				0.9857				0.5749			
RFGHG, RFSOX, & RFBC cause TEMP	0.0053				0.0921				0.0196			
RFVOL causes TEMP	0.0122				0.0044				0.0014			
RFSOL cause TEMP	0.2967				0.2544				0.2940			
RFVOL & RFSOL cause TEMP	0.0127				0.0148				0.0045			
TEMP causes RFGHG	0.0058				0.0062				0.0142			

Figures are p-values for rejecting the null hypothesis of no causation. See Table 1 for variable codes

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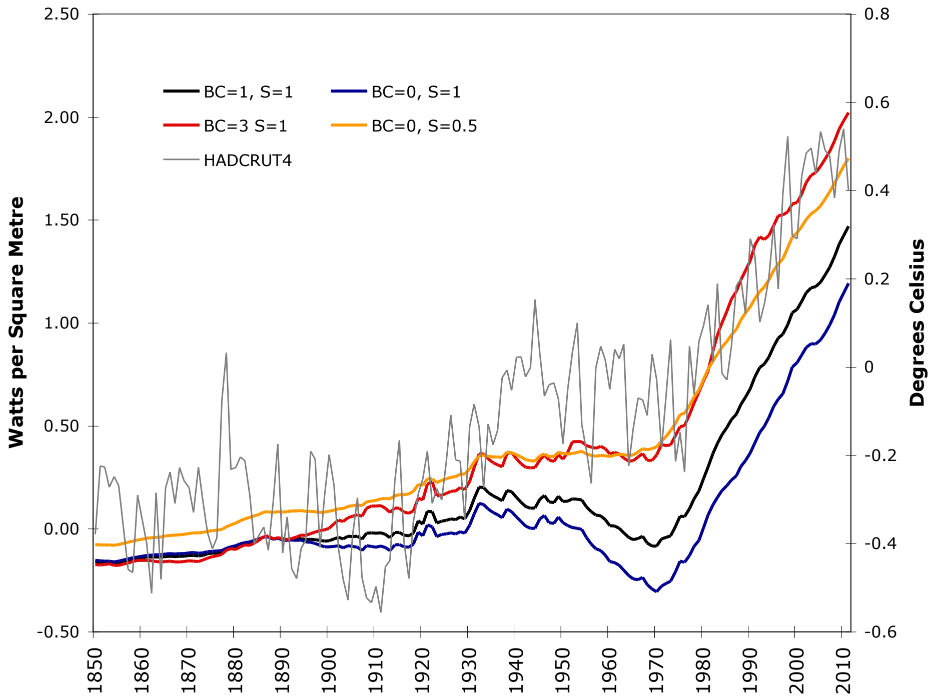
Figure 1. Anthropogenic and Natural Forcing 1850-2011

Radiative forcing of zero is given by greenhouse gases in 1850 with no aerosols. **a**. Total anthropogenic forcing under our four scenarios and global temperature. **b**. Total anthropogenic and natural forcing under the four scenarios.

a.



b.

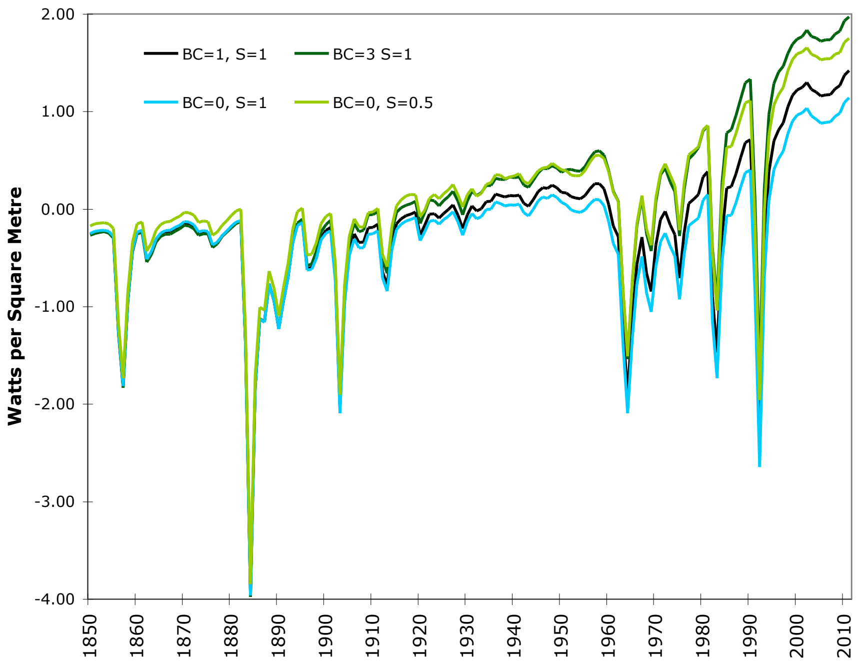


Figure 2. Global Temperature and Ocean Heat Content 1850-2011