Journal of Finance and Economics
Volume 2, Issue 4 (2014), 17-24
ISSN 2291-4951 E-ISSN 2291-496X
Published by Science and Education Centre of North America

Global Warming: An Econometric Analysis

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DOI: 10.12735/jfe.v2i4p17 URL: http://dx.doi.org/10.12735/jfe.v2i4p17

Abstract

An econometric analysis is provided of the system of relationships involving global CO_2 emissions, atmospheric concentration of anthropogenic CO_2, and global surface temperature increase since the preindustrial era. Empirical methods used are feasible generalized least squares and generalized method of moments. It is found that global surface temperature increase is estimated to have a positive effect on the CO_2 absorption capacity of the environment.

JEL Classifications: C39, Q54

Keywords: anthropogenic CO_2, atmospheric CO_2 concentration, CO_2 emissions, econometric analysis, global warming

1. Introduction

There has been a considerable amount of science devoted to the study of the climate effects of anthropogenic greenhouse gas (GHG) emissions and their increasing concentration in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC), in particular, has prepared its Fifth Assessment Report (AR5) that includes three Working Group Reports and a Synthesis Report. In addition, there continue to be numerous contributions to the academic literature on the subject. Climate change is a well-studied phenomenon.

Even so, there remain unresolved issues regarding climate change and its attendant global warming. An open matter of particular importance is whether increasing temperatures are affecting the ability of the earth's terrestrial and oceanic environments to absorb CO_2, and if so, whether the effect is positive or negative.

The present study aims to shed light on the global warming issue, in particular the effect of warming on the earth's ability to absorb CO_2, through econometric analysis of available data on fossil-fuel CO_2 emissions, atmospheric concentration of CO_2, and global temperature increase. Econometric analysis can be insightful, in that such analysis is effective in the empirical study of systems of relationships, and the interaction involving CO_2 and global temperature is such a system.

The paper proceeds as follows. The next section summarizes the state of knowledge regarding global warming, and is followed by sections that describe the data, outline the estimation model, provide estimation results, and draw implications. A conclusions section finishes the paper.

2. State of Knowledge

This section provides a summary of the essential basics of what is known, and not known, about global warming related to anthropogenic GHG emissions. Stocker *et al.* (2013) provide a thorough assessment of the current state of scientific knowledge.

There are two critical dynamic processes at work that are interrelated: (1) changes in atmospheric concentrations of GHG; (2) changes in global surface temperature.

2.1 Changes in Atmospheric Concentrations of GHG

Concentrations of long-lived GHG, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), have increased substantially since the onset of the industrial revolution in the eighteenth century. The increase is due to human activities, largely the burning of fossil fuels. The biggest contributor to the radiative forcing of the climate system, and thereby global warming, is CO_2, and so the understanding of the influence of CO_2 on global surface temperature is especially critical (Stocker *et al.*, 2013, Ch. 8).

The earth's terrestrial and ocean environments are able to absorb CO_2. After CO_2 enters the atmosphere, a third to half of the CO_2 pulse is absorbed by land and ocean, with the remainder removed through reaction with calcium carbonate over a few thousand years, and silicate weathering over several hundred thousand years (Stocker *et al.*, 2013, Ch. 6).

It is possible that the warming of the earth's atmosphere is affecting the environment's ability to absorb CO_2. However, this is not well understood. Nor is it well understood, if warming does affect absorption capacity, whether the effect is positive or negative (Hansen, Kharecha, & Sato, 2013). Studies offer apparently conflicting conclusions. Piao *et al.* (2008) and Zhao and Running (2010) appear to find reduction in terrestrial carbon absorption in recent years, while Le Quéré *et al.* (2007) and Schuster and Watson (2007) estimate decline in the ocean CO_2 sink. On the other hand, Knorr (2009) can find no trend, and Sarmiento *et al.* (2010) and Ballantyne, Alden, Miller, Tans, and White (2012) observe increase in the environment's net CO_2 uptake since 1960. A contribution of the present study is to shed an econometric light on this important issue.

2.2 Changes in Global Surface Temperature

The earth's surface temperature is considered to adjust gradually to an increase in atmospheric CO_2 toward an equilibrium. There are two key aspects of the relationship: the equilibrium temperature, and the rate of adjustment toward the equilibrium.

Much effort has been dedicated, through a combination of historical temperature data analyses and model simulations, to establish a range for "equilibrium climate sensitivity", defined as the global mean warming for a doubling of CO_2 from the concentration level in the year 1750. The IPCC's Fifth Assessment Report (AR5) concludes that equilibrium climate sensitivity "…is *likely* in the range 1.5^{o}C to 4.5^{o}C…" (Stocker *et al.*, 2013, p. 1033). There remains uncertainty about the precise ultimate change in temperature due to increasing atmospheric CO_2.

The likely rate of adjustment to equilibrium can be gleaned from simulations done for IPCC's AR5. In particular, a scenario referred to as RCP4.5 shows stabilization in atmospheric CO_2 concentration by about the year 2100, yet, for that scenario, mean surface air temperature is projected to continue to rise by .5^{o}C by 2200 and .7^{o}C by 2300 (Stocker *et al.*, 2013, Table 12.2). The two data points in the temperature projections, coupled with an assumed exponential adjustment relationship, suggest an annual adjustment rate of just about .01.

3. Data

Data for the study are readily available from various sources.

Global fossil-fuel CO_2 emissions data are provided, on an annual basis from 1751 through 2012, by U.S. Department of Energy's Carbon Dioxide Information Analysis Center (CDIAC) http://cdiac.ornl.gov/trends/emis/meth_reg.html. Emissions are measured in millions of metric tons of carbon.

Annual atmospheric CO_2 concentration measurements at Mauna Loa are available from Earth System Research Laboratory of U.S. Department of Commerce's National Oceanic & Atmospheric Administration http://www.esrl.noaa.gov/gmd/ccgg/trends/, and are used with the permission of that facility. CO_2 concentration is measured as a dry mole fraction, number of molecules of CO_2 divided by number of all molecules in air after water vapor has been removed, and expressed as parts per million (ppm). Data are also available from 1980 on a global basis, but since the Mauna Loa data closely match the global data, the Mauna Loa concentration data from 1959 are used in the analysis. Further, since the interest is in anthropogenic CO_2, we subtract the preindustrial concentration level of 280 from the data.

Annual global surface temperatures are from National Aeronautics and Space Administration's Goddard Institute for Space Studies http://data.giss.nasa.gov/gistemp. Temperature is measured in units of .01^{o}C, and is expressed as the difference from the first year available, 1880, the temperature for which year being used as a proxy for the preindustrial temperature level.

Finally, since annual variability in both temperature and CO_2 concentration are correlated with the Niño 3.4 index (Hansen, Ruedy, Sato, & Lo, 2010; Hansen *et al.*, 2013), that index, expressed as anomalies from the base period 1981-2010, is used as a covariate for both relationships. The data on the Niño 3.4 anomalies are obtained from the National Weather Service's Climate Prediction Center http://www.cpc.ncep.noaa.gov/data/indices. Another index http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao_index.html is the AO (Arctic Oscillation) index, which is related to temperatures in North America and Eurasia (Thompson, Wallace, Jones, & Kennedy, 2009; Thompson, Wallace, & Hegerl, 2000), and so is used as a covariate in the temperature relationship. Both indices are available on a monthly basis, and are annualized by summing over the 12 months of the year.

Merging the various data provides an annual data base for the years 1959 through 2012.

4. Estimation Model

Define the following variables:

$C_t =$ atmospheric concentration of anthropogenic CO_2 in year t

$T_t =$ global surface temperature increase over 1880 in year t

$M_t =$ global CO_2 emissions in year t

$N_t =$ Niño 3.4 index level in year t

$A_t =$ AO index level in year t.

Dependent variables for the econometric analysis are the annual changes in CO_2 concentration and temperature: $\Delta C_t = C_t - C_{t-1}$, $\Delta T_t = T_t - T_{t-1}$.

The global warming process is depicted as a system of two equations:

$$\begin{aligned} \Delta C_t &= \alpha M_t + \beta N_{t-1} - \left(\gamma + \delta T_{t-1}\right) C_{t-1} + \mu_t \\ \Delta T_t &= \varepsilon N_{t-1} + \zeta A_{t-1} + \eta \left(\theta C_{t-1} - T_{t-1}\right) + \nu_t \end{aligned} \tag{1}$$

where $\alpha, \beta, \gamma, \delta, \varepsilon, \zeta, \eta, \theta$ are parameters to be estimated, and μ_t, ν_t are random disturbances that are allowed to be correlated.

The first equation in the system (1) shows that the annual change in atmospheric CO_2 concentration derives positively from CO_2 emissions and negatively from environmental absorption of atmospheric CO_2. Annual change in the concentration is also affected by the Niño index. The CO_2 absorption rate depends on the temperature level, where the sign of the δ parameter can be positive or negative, and which sign will indicate whether temperature has a positive or negative influence on the absorption rate. The model (1) allows the data to indicate the direction of the influence.

The second equation in (1) shows that annual change in temperature is a partial adjustment to the difference between the equilibrium temperature increase, which equilibrium depends on the current CO_2 concentration level, and the current temperature increase. Annual temperature change is also influenced by the Niño and AO indices.

5. Estimation

Estimation of the nonlinear system (1) is accomplished using the Stata data analysis package. Two estimation approaches are used. The first is maximum likelihood, specifically feasible generalized least squares (FGLS), which allows the random disturbances for the two equations to be correlated. The results from this estimation are shown in Table 1.

Table 1. FGLS estimation

Coefficient	Estimate	Standard error	z
α	.0003863	.0001304	2.96
β	.0341525	.0070081	4.87
γ	.0053833	.0115154	0.47
δ	.0000875	.0000309	2.83
ε	.4941749	.1909941	2.59
ζ	.3766008	.2272498	1.66
η	.6918035	.1176141	5.88
θ	.7446362	.0275520	27.03

All coefficient estimates for the FGLS estimation are positive and statistically significant, except for the base CO_2 absorption rate, while the estimate for the AO effect on temperature change is significant at only the .10 level. In particular, the estimate for the effect of temperature on the CO_2 absorption rate is positive and significant. The point estimate values appear reasonable, except for that of the temperature adjustment parameter η, which is much higher than the .01 value suggested by the RCP4.5 scenario.

The second estimation approach allows for correlation of regressors with the random disturbances. This is likely the case, due to the interrelationship of atmospheric CO_2 and temperature exhibited in the system (1). The appropriate approach for this possibility is generalized method of moments (GMM). Instruments are needed for this approach, and the following are used as instruments in the estimation: M_t, N_{t-1}, A_{t-1}, year, (year – 1959)^2. The estimation results are shown in Table 2.

Table 2. GMM estimation

Coefficient	Estimate	Standard error	z
α	.0002506	.0001166	2.15
β	.0378597	.0071695	5.28
γ	−.0062871	.0102935	−0.61
δ	.0000871	.0000245	3.55
ε	.2136107	.2172791	0.98
ζ	.1606706	.2552154	0.63
η	.1027354	.2237836	0.46
θ	.8803589	.3651523	2.41

The estimates for the CO_2 concentration relationship are similar to those for FGLS estimation. In particular, it is especially noteworthy that the estimated effect of temperature on the CO_2 absorption rate is positive. Increase in global surface temperature appears to enhance the environment's ability to absorb CO_2.

For the temperature relationship, the parameter estimates for GMM differ considerably from those for FGLS. In particular, the estimate for the annual temperature adjustment parameter is much smaller; in addition, the .01 value from the RCP4.5 scenario is within the 95% confidence interval with GMM estimation, while it falls outside the interval with FGLS estimation.

6. Implications

Long-run implications for global temperatures can be drawn from the model (1) and its parameter estimates. Consider the following continuous-time version of the model that disregards the short-term Niño and AO effects and random disturbances:

$$\begin{aligned} \frac{dC}{dt} &= \alpha M(t) - \big(\gamma + \delta T(t)\big) C(t) \\ \frac{dT}{dt} &= \eta\big(\theta C(t) - T(t)\big). \end{aligned} \tag{2}$$

For the system (2) to achieve a steady state, emissions $M(t)$ must stabilize; assume such at a value of M_s, so that (2) becomes

$$\frac{dC}{dt} = \alpha M_s - \left(\gamma + \delta T(t)\right) C(t)$$
$$\frac{dT}{dt} = \eta\left(\theta C(t) - T(t)\right). \tag{3}$$

Setting $dC/dt = dT/dt = 0$ achieves the following steady-state values for CO_2 concentration and temperature increase:

$$C_\infty = \frac{1}{2\delta\theta}\left(-\gamma \pm \sqrt{\gamma^2 + 4\alpha\delta\theta M_s}\right)$$
$$T_\infty = \frac{1}{2\delta}\left(-\gamma \pm \sqrt{\gamma^2 + 4\alpha\delta\theta M_s}\right). \tag{4}$$

It is straightforward to show that only the larger, positive, steady-state is feasible with nonnegative initial values $C(0)$, $T(0)$:

$$C_\infty = \frac{1}{2\delta\theta}\left(-\gamma + \sqrt{\gamma^2 + 4\alpha\delta\theta M_s}\right)$$
$$T_\infty = \frac{1}{2\delta}\left(-\gamma + \sqrt{\gamma^2 + 4\alpha\delta\theta M_s}\right). \tag{5}$$

Assume the GMM point estimates for the parameters α, δ, θ, except set $\gamma = 0$, since that parameter estimate is not statistically different from zero. This implies the following steady-state relationships:

$$C_\infty = 1.81\sqrt{M_s}$$
$$T_\infty = 1.59\sqrt{M_s} \tag{6}$$

and it can be shown that the steady state (6) is asymptotically stable. Since in the estimation temperature is measured in terms of .01°C, the following converts the steady-state temperature relationship in terms of °C:

$$T_\infty = .0159\sqrt{M_s}. \tag{7}$$

The relationship (7) is depicted in Figure 1. In particular, if global emissions could be stabilized at the current level, around 10 billion metric tons, the global surface temperature would be expected to rise to 1.59°C above the preindustrial level.

7. Conclusions

This paper provides an econometric analysis of the system of relationships involving global CO_2 emissions, atmospheric concentration of anthropogenic CO_2, and global surface temperature increase.

A key finding is that, in both FGLS and GMM estimation of the system, temperature is estimated to have a positive effect on the capacity of the earth's environment to absorb CO_2.

Implications are drawn regarding the ultimate temperature consequences of differing levels of stabilized CO_2 emissions.

It is important to understand the nature of the interactive relationships that lead to global warming. The econometric analysis herein provides a contribution to such understanding.

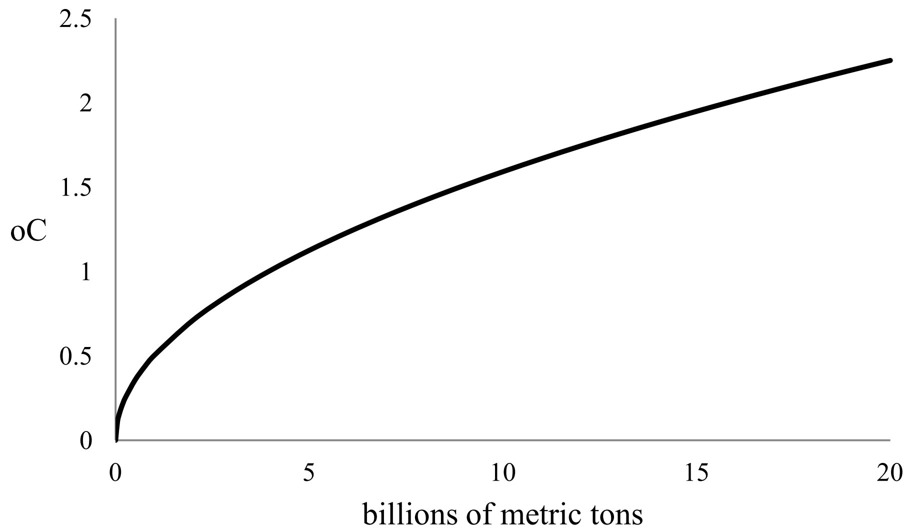

Figure 1. Steady-state global surface temperature

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