ENVIRONMENTAL SCIENCE & POLICY 21 (2012) 50–62

Available online at www.sciencedirect.com

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Climate change and the world economy: short-run determinants of atmospheric CO_2

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ARTICLE INFO

Article history:
Received 31 January 2012
Received in revised form
23 March 2012
Accepted 23 March 2012
Published on line

Keywords:
Climate change
CO_2 atmospheric concentrations
World economic growth
World population

ABSTRACT

Volcanic eruptions, the *El Niño* Southern oscillation (ENSO), world population, and the world economy are the four variables usually discussed as influencing the short-run changes in CO_2 atmospheric levels through their influence on CO_2 emissions and sinks. Using proper procedures of detrending, we do not find any observable relation between the short-term growth of world population and the increase of CO_2 concentrations. Results suggest that the link between volcanic eruptions, ENSO activity, and CO_2 concentrations may be confounded by the coincidence of the Pinatubo eruption with the breakdown of the economies of the Soviet Bloc in the early 1990s. Changes in world GDP (WGDP) have a significant effect on CO_2 concentrations, so that years of above-trend WGDP are years of greater rise of CO_2 concentrations. Measuring WGDP in constant US dollars of 2000, for each trillion WGDP deviates from trend, the atmospheric CO_2 concentration has deviated from trend, in the same direction, about half a part per million.

1. Introduction

Though climate change is related to several greenhouse gases (GHG), including halocarbons, nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2), it is the consensus in the scientific community that CO_2 is the most important anthropogenic GHG, so that increasing atmospheric levels of CO_2 represent the key factor to understand and explain global warming (Solomon et al., 2007). It is therefore significant that the worldwide recession of 2007–2009 has been viewed by natural scientists as a cause of reduction in CO_2 emissions and also as a likely reason explaining that the 2009 increase in atmospheric CO_2 was quite low (Friedlingstein et al., 2010). However, in the geosciences community, short-run annual changes in atmospheric levels of CO_2 are usually seen as largely determined by two natural phenomena: volcanic eruptions and the so-called *El Niño* Southern oscillation (ENSO) (Raupach et al., 2008; Kaufmann et al., 2006; Le Quéré et al., 2009). The dependence of CO_2 concentrations on natural phenomena would be the reason that, for instance, the observed CO_2 increase in the atmosphere averaged over several years accounts for only about 56% of the fossil fuel input, and this despite the fact that deforestation continues (Hansen, 2010).

Since the 1990s, the field of economics has been quite divided on the relation between economic growth and CO_2 emissions and also on the implications of global warming and the best policies to prevent climate change (Holtz-Eakin and Selden, 1995; Stern, 2007; Spash, 2002; McCormick, 2004; Nordhaus, 2008). A common hypothesis among economists has been that the relation between economic growth, air pollutants in general, and CO_2 in particular has the shape of an inverted U, the EKC or environmental Kuznets curve. If CO_2 emissions followed an EKC, they would first increase and then decrease with the growth of the gross domestic product (GDP)

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http://dx.doi.org/10.1016/j.envsci.2012.03.008

(Grübler and Nakicenovic, 1996; Nakicenovic, 1996; Sun and Meristo, 1999; Roberts and Grimes, 1997; Schmalensee et al., 1998). Controversy on the EKC for CO_2 has arisen because other economists have not been able to find any evidence in favor of this hypothesis or have disputed, on both theoretical and empirical grounds, the goodness of fit of EKC models for CO_2 and the extent to which particular results are generalizable (Ekins, 1997; de Bruyn et al., 1998; Stern and Common, 2001; Stern, 2004; Dijkgraaf and Vollebergh, 1998, 2005; Richmond and Kaufmann, 2006; Wagner, 2008; Müller-Fürstenberger and Wagner, 2007; Arrow et al., 1995).

Estimates of CO_2 global emissions increasing annually 1.1% during the 1990s and over 3% in 2000–2004 (Raupach et al., 2007) and emissions from fossil fuel burning increasing by 29% between 2000 and 2008 (Le Quéré et al., 2009) seem inconsistent with an EKC for CO_2. In fact, the growth of emissions since 2000 has been greater than for the most fossil-fuel-intensive emissions scenarios developed in the late 1990s by the Intergovernmental Panel on Climate Change. At both the national and the global level, evidence is mounting on the link between increased production of goods and services and growth of GHG emissions, CO_2 in particular (Raupach et al., 2007; Quadrelli and Peterson, 2007; Roca and Alcántara, 2001; Tol et al., 2009). With evidence in favor of an EKC for CO_2 largely disputed and with emissions increasing in recent years, the emerging consensus seems to be that the curve is shaped as an N rather than as an inverted U (de Bruyn et al., 1998; Dinda et al., 2004; Martinez-Zarzoso and Bengochea-Morancho, 2004).

Atmospheric concentration of CO_2, rather than the level of emissions, is the variable directly determining the global climate. Change in the atmospheric concentration is the result of emissions—mainly from burning fossil fuels, since natural emissions from volcanoes are estimated as a tiny fraction of man-made emissions—minus removals by natural sinks. Many investigations have studied how natural factors affect the short-run evolution of CO_2 concentrations, but to our knowledge no investigation has attempted to connect the evolution of CO_2 concentrations with changes in the global economy.

We believe that studying the link between the economy and climate change, focusing on levels of atmospheric CO_2 rather than CO_2 anthropogenic emissions, is a better methodological choice because (a) global climate depends directly on CO_2 concentrations, and only indirectly on CO_2 emissions; (b) CO_2 concentrations depend on factors beyond emissions (natural emissions and sinks of CO_2); and (c) the *measurement* of atmospheric levels of CO_2 is much more accurate and reliable than the *estimation* of emissions (from statistics on fuel consumption, exports, imports, etc.), which is likely subject to considerable margins of error (Nordhaus, 1994, p. 27; Nisbet and Weiss, 2010).

Population growth and economic activity are sometimes mentioned as being linked to the short-term changes in CO_2 atmospheric levels, but we are not aware of any direct attempt to establish whether there is a leading factor in the short-term growth of atmospheric CO_2, or how global economic activities and population may be related to CO_2 atmospheric concentrations both in the short run and in the long run.

The purpose of our investigation was to explore the impact of the natural and social variables that have been considered as long-run and short-run determinants of atmospheric CO_2. The use of cointegration to model the long-term associations between CO_2 concentrations, the volume of the world economy, and the size of the world population yielded inconclusive results, and in this paper we report our analysis of the variables that in the short run are potentially linked with the increase in CO_2 concentrations (i.e., volcanic activity, ENSO, the world economy, and the world population).

In the next section we discuss the trends and rates of change in atmospheric CO_2 levels and the four variables that potentially determine its short-run growth. Section 3 presents the statistical analysis, Section 4 discusses the results, and Section 5 concludes. An Appendix A provides details about the data.

2. Atmospheric CO_2 and its potential explanatory factors

CO_2 concentrations continuously measured in dry air on the Hawaiian volcano Mauna Loa since March 1958 (Keeling and Whorf, 2005) constitute the longest series of CO_2 levels documenting the changing composition of the atmosphere. What is now known as the Keeling curve reveals a rising trend over a quite regular oscillating seasonal pattern (Fig. 1), attributed to differences in the ability of photosynthesis and respiration of the terrestrial biosphere and other sinks of CO_2 to absorb the gas through the annual seasonal cycle (Conway et al., 1994). Annual mean atmospheric concentrations of CO_2 computed from the Mauna Loa records reveal an almost linear increase of CO_2 atmospheric levels since 1959 to the present (Fig. 2).

A number of estimates of the global output measured in money, or "world GDP" (WGDP) and world population are available (see Appendix A on data). According to World Bank estimates, WGDP measured in 2000 US dollars increased almost six-fold, from 7.2 trillion in 1960 to 41.3 trillion in 2010 (Fig. 2). World population estimates reached 7.0 billion in 2011, more than doubling from the level of 3.0 billion in 1960.

ENSO activity refers to a pattern of climate changes (with associated floods and droughts) across the tropical Pacific Ocean, which recurs at intervals varying from 3 to 7 years. Between 1960 and 2010, the index measuring annual ENSO activity (Fig. 3) varied between −1.49 and 2.03. Negative values correspond to cold years ("La Niña"), and positive values to warm years ("El Niño"). ENSO activity is thought to be linked to changes in atmospheric CO_2 levels because warmer years increase the capture of CO_2 by raising the growth rate of trees (Ciais et al., 2005), and perhaps also by strengthening the capture of CO_2 by the oceans (Krakauer and Randerson, 2003).

Volcanoes emit CO_2, and atmospheric CO_2 in preindustrial times is considered to have originated from volcanic sources (Kasting and Walker, 1992). The eruption in March–April 2010 of the Icelandic volcano Eyjafjallajoekull emitted about 150,000 tonnes of CO_2 per day into the atmosphere.[1] However, volcanic activity is considered to be a factor reducing

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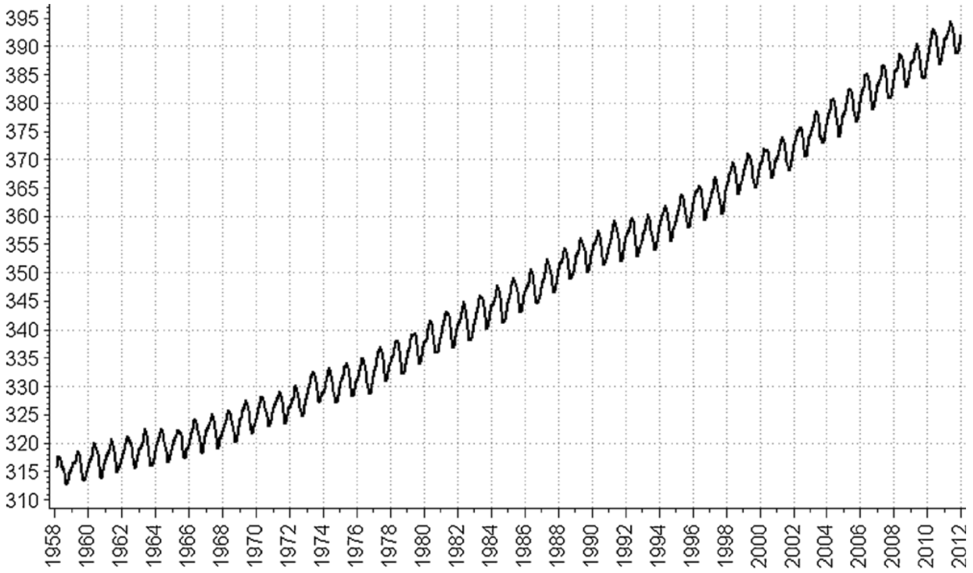
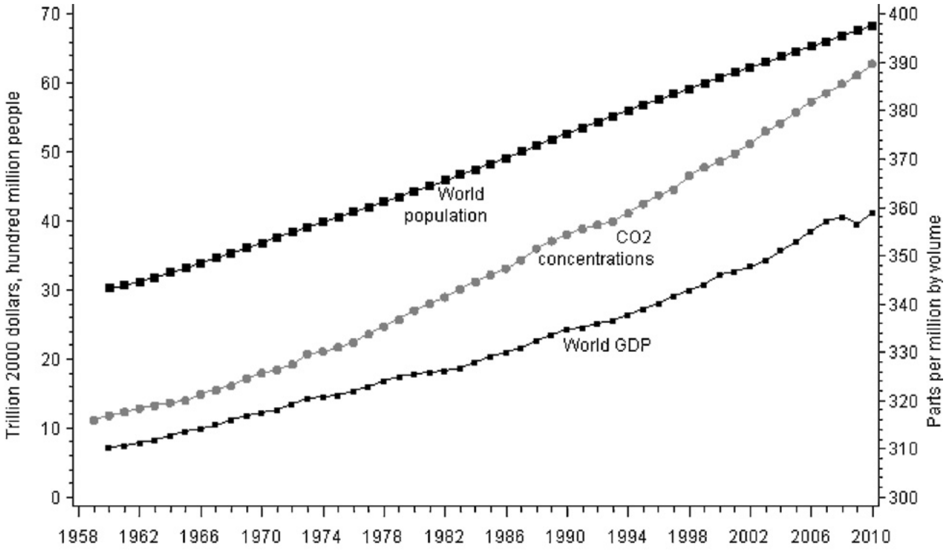
[1] It was also estimated that the grounding of European flights generated by the Eyjafjallajoekull eruption avoided an estimated 344,000 tonnes of CO_2 emissions per day (UNEP, 2011).



Source: CO_2Now.org.

Fig. 1 – Atmospheric CO_2 (monthly average) as measured in air samples collected at Mauna Loa, Hawaii (Keeling curve) from February 1958 to February 2012. Units are parts per million by volume. Estimated preindustrial concentrations, at levels between 200 and 300 ppm, would be far out of the graph.



Source: CO_2Now.org (CO_2 concentrations) and World Bank database (world GDP and population).

Fig. 2 – Mean annual atmospheric concentrations of CO_2 (right scale), world gross "domestic" product, and world population (left scale).

atmospheric CO_2 levels, by means of atmospheric ash which would increase diffuse solar radiation and tree growth (Trenberth and Dai, 2007). Between 1958 and 2009, the index of volcanic activity (Fig. 3) varied between zero and 3.65.

Neither ENSO activity nor the volcanic index shows any obvious trend.

Throughout the period 1960–2010, CO_2 atmospheric concentrations increased annually by 1.45 ± 0.58 ppm (mean ± standard deviation), while WGDP grew by 0.68 ± 0.42 trillion dollars per year, and the world population expanded annually by 76.3 ± 7.9 million (Figs. 2 and 3). Annual changes in these variables, however, reveal major changes in the rates of growth. First, the annual change in CO_2 concentration has itself been rising (Fig. 3). While concentrations grew annually by 1.14 ± 0.48 ppm in 1958–1984, in 1985–2011 they increased by 1.74 ± 0.52 ppm per year. Second, since the output of

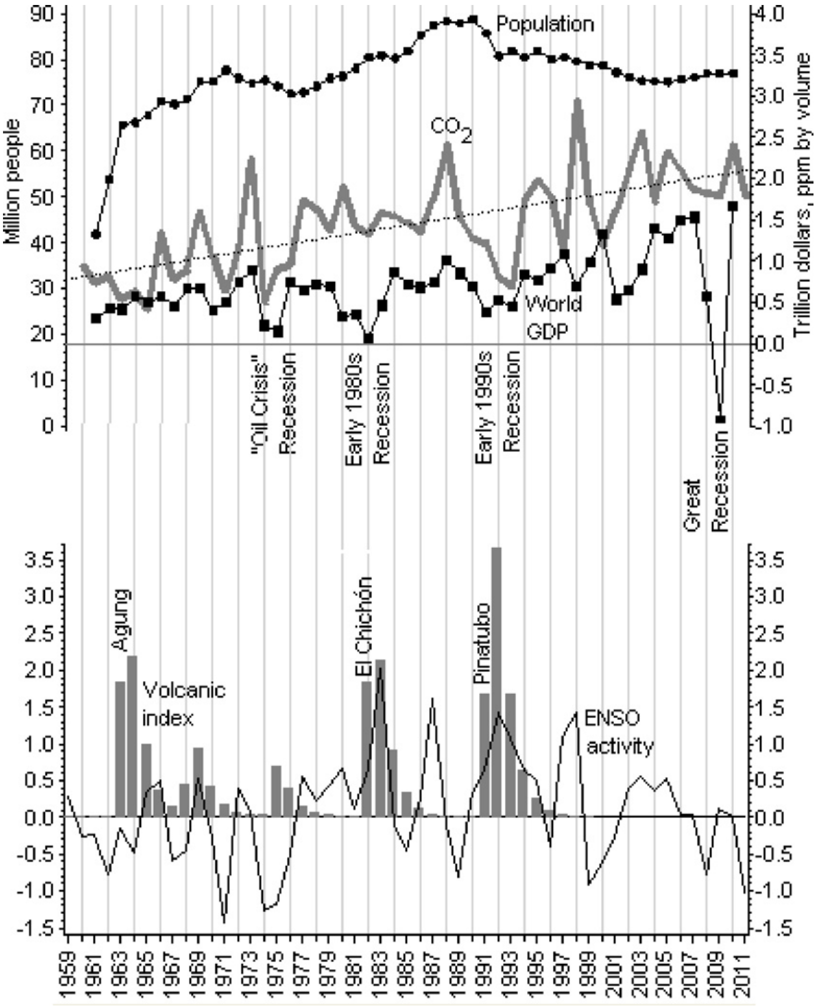


Fig. 3 – Annual changes in the world population, in the mean atmospheric concentration of CO_2 (the dotted line is a linear trend), and in world GDP (top panel) plotted together with the volcanic index and the mean annual ENSO activity (bottom panel). Major global recessions (periods of low or negative growth of world GDP) and major volcanic eruptions are indicated. *Sources*: See Appendix A.

national economies, averaging expansions and contractions, grows in the long run at a constant rate, the annual absolute increase in WGDP also tends to be larger over time. Indeed, WGDP grew on average 0.51 ± 0.22 trillion/year before 1985 and 0.84 ± 0.51 trillion/year in 1985–2010, with a big deviation from trend in 2008–2009 (Figs. 2 and 3), when it shrank by 0.94 trillion in the so-called Great Recession. Third, the estimated annual growth of world population also increased, from 71.9 ± 8.6 million before 1985 to 80.3 ± 4.4 million in 1985–2010. The rate of world demographic growth, however, which had strongly increased from the late 1950s to the early 1990s (Fig. 3), decreased slightly thereafter.

If rising atmospheric CO_2 is due to human activities, changes through time in world population or global economic activity should affect how fast atmospheric CO_2 rises. On the contrary, the curves of annual growth of world population and atmospheric CO_2 (Fig. 3) do not show any apparent association. The annual increase in CO_2 concentration compared with the annual increase in WGDP, however, does seem to reveal quite a parallel evolution before the mid 1990s. Peaks of WGDP growth (in 1973 and 1988) coincide with peaks in the growth of CO_2 concentrations (Fig. 3) and troughs in CO_2 growth coincide with troughs in WGDP corresponding to the recessions of 1974–1975 (the ‘‘oil crisis’’ recession), the early 1980s, and the late 1980s–early 1990s. The large drop in the annual growth of CO_2 concentrations in 1988–1993 coincided with the economic collapse of the old USSR and its Eastern European allies, and with major economic downturns in many other countries. The rate of growth of the global economy that peaked in 1988 (Fig. 3) then dropped steadily, reaching a decadal minimum in 1991 and remaining at very low levels for two more years. In summary, both world economic growth and the annual increase in CO_2 atmospheric concentrations dropped sharply in 1988–1993, similar to what had occurred in 1973–1974 and in 1980–1982 (Fig. 3). After the mid 1990s, the parallelism between the curves of annual growth of the world economy and CO_2 concentrations disappears, but in 2007–2010 the V pattern (the Great Recession) in WGDP is paralleled by a U or J pattern in the curve of growth of CO_2 atmospheric levels (Fig. 3).

Table 1 – Correlations of the annual series of CO_2 atmospheric concentrations with the annual series of world GDP (WGDP), world population, the volcanic index, and the index of *El Niño* Southern oscillation (ENSO) activity, with the two series detrended by the same method, as indicated.

		Correlations			Sample size[a]
Detrending method	Variable	Lag −1	Lag 0	Lag +1	
A. Subtraction of a HP trend computed with $\gamma = 100$	WGDP	0.36^{**}	0.40^{**}	0.21	50–53
	Population	0.18	0.15	0.04	
	Volcanic index	0.12	−0.22	-0.49^{***}	
	ENSO index	-0.45^{*}	−0.11	0.28^{*}	
B. Subtraction of a HP trend computed with $\gamma = 6.25$	WGDP	$0.24^{\dagger}$	0.28^{*}	0.03	50–53
	Population	0.05	0.06	0.02	
	Volcanic index	0.11	−0.14	-0.37^{**}	
	ENSO index	-0.54^{***}	−0.06	0.44^{***}	
C. Subtraction of a moving mean with window size $w = 7$	WGDP	0.31^{*}	0.39^{**}	0.20	42–46
	Population	0.16	0.05	−0.01	
	Volcanic Index	0.15	−0.17	-0.39^{**}	
	ENSO index	-0.49^{***}	−0.09	0.41^{**}	
D. Subtraction of a moving mean with window size $w = 9$	WGDP	0.36^{*}	0.46^{**}	0.31^{*}	40–44
	Population	0.16	0.06	−0.01	
	Volcanic index	0.15	−0.19	-0.50^{**}	
	ENSO index	-0.42^{**}	−0.08	$0.28^{\dagger}$	

[a] Inclusion of lags or leads sometimes eliminates data, so that the correlations in each panel are based in a slightly different sample size.
* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
† $P < 0.1$.

Short-run oscillations of the annual increase in CO_2 concentrations have frequently been explained by ENSO activity and volcanic eruptions (Conway et al., 1994; Friedlingstein et al., 2010), but the link between annual changes in ENSO or volcanic activity and annual changes in atmospheric CO_2 is far from obvious. For instance, a peak in ENSO activity in 1992 coincided with a sharp drop in the annual increase in CO_2 levels (Fig. 3), but the next peak in ENSO activity, in 1998, coincided with a large increase in CO_2 concentrations.

Early suggestions that the economic disruption associated with the collapse of the former Soviet Bloc in the early 1990s may have resulted in a major decrease of CO_2 emissions from Eastern Europe (Flavin, 1992) were considered plausible (Conway et al., 1994), though not likely to explain the decline of the growth rate of CO_2 concentrations in the early 1990s. Today the connection between the Soviet collapse and a decline in world *emissions* of CO_2 is generally accepted (Raupach et al., 2007; Quadrelli and Peterson, 2007) but, to our knowledge, no one has proposed that the fall in the annual increase in CO_2 concentrations during the early 1990s might be linked with the global downturn of world economic activity in those years; neither has there emerged quantitative evidence that changes in the global economy have a statistically detectable impact on CO_2 atmospheric concentrations. That is what we will now show.

3. Statistical analysis

3.1. *Correlation analysis*

To gauge the degree of coincidental or lagged oscillation suggestive of a causal short-run link, we computed the correlations of CO_2 concentrations with each of the other four variables. Since relevant correlations may occur coincidentally or lagged, we examined correlations at several lags. Because the annual increase of CO_2 concentrations has been growing over time (Fig. 3), detrending the series of CO_2 levels by either taking first differences or subtracting a linear trend—the two standard methods of detrending—are *not* appropriate ways of detrending.[2] For that reason we used four procedures of non-linear detrending by subtracting trends computed both with the Hodrick–Prescott (HP) filter and with centered moving means. The HP filter was applied with smoothing parameters $\gamma = 100$ and $\gamma = 6.25$, the two extremes of the range of values recommended by various authors to detrend series of annual data (Ravn and Uhlig, 2002; Maravall and del Río, 2007). The moving means were computed with windows of size 7 and size 9, which a priori seem to be appropriate to deal with annual data.

Correlations of CO_2 concentrations with WGDP at lag 0 are positive and statistically significant ($P < 0.05$) for all methods of detrending and strongly significant ($P < 0.01$) for three of them (Table 1). The strongest correlations with CO_2 are at lag 0, but there are also significant correlations at lags −1 and 1, all of them positive. This is evidence strongly suggestive that years in which WGDP grows above or below trend are respectively

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[2] The augmented Dickey–Fuller (ADF) test for unit roots does not reject the null when applied to the annual series of CO_2 concentrations. When the series is differenced, the ADF test does not reject the null in most specifications, but the null is rejected in all specifications when CO_2 annual concentration is in second differences, so that the series of CO_2 annual concentrations appears to be I(2).

years of above-trend or below-trend increase in CO_2 concentrations.

Correlations of CO_2 with world population are statistically indistinguishable from zero for all four methods of detrending and all lags.[3] No evidence supports the existence of a short-term link between population growth and the growth of CO_2 atmospheric concentrations.

Neither volcanic activity nor the ENSO index reveal any significant correlation with detrended CO_2 concentrations at lag 0, but they do reveal significant correlations with CO_2 at lag 1.

The volcanic index has significant negative correlations with CO_2 concentrations at lag 1 but not at lag 0 or lag -1. This seems to be logical, since it suggests that volcanic activity has an effect on CO_2 concentrations one year after it occurs. It would be difficult to explain a significant correlation at lag -1 that would be suggestive of CO_2 concentrations being influenced by volcanic activity one year before the volcanic activity occurs.

Finally, the ENSO index reveals significant correlations with CO_2 at lags -1 and 1, *but not at* lag 0. Since the correlations are negative at lag -1 and positive at lag 1, the pattern is perfectly consistent with an effect of ENSO activity on natural sinks of CO_2. In the year preceding high ENSO activity, there is high sequestration of CO_2 and concentrations tend to grow below average, while in the year following high ENSO activity the opposite occurs, and CO_2 concentrations grow above trend. While volcanic eruptions are discontinuous phenomena, ENSO activity is a continuous climate oscillation and it seems therefore reasonable to find an effect on CO_2 concentrations at a negative lag.

In summary, correlations provide evidence in favor of the following: (1) during years of above-trend WGDP, there is above-trend growth of CO_2 concentrations; (2) one year after above-trend ENSO activity, the growth of CO_2 concentrations is above trend; and (3) one year after increased volcanic activity there is below-trend growth of CO_2 concentrations. These bivariate relations can be examined all together in multivariate regression models.

3.2. *Regression analysis*

We analyzed models in which CO_2 concentrations are regressed on both a constant and a series of WGDP, ENSO activity, and the volcanic index, with all time series detrended by the same method and explanatory variables entering in the models at several lags. By minimizing the usual measures of goodness of fit—the Schwartz Bayesian criterion (SBC), the Akaike information criterion (AIC), or AIC corrected (AICC)—we concluded that WGDP must be entered in the models only at lag 0, while ENSO activity must be entered at lags 0 and 1, and volcanic activity at lags 0, 1, and 2.

The statistical evidence (Table 2) is consistent with WGDP and ENSO activity raising CO_2 concentrations and volcanic activity decreasing them. That is, the greater the annual increase in WGDP or ENSO activity, the greater the annual increase in CO_2 concentrations, while higher volcanic activity reduces the rate of growth of CO_2 levels. The statistically significant effects occur at lag 0 for WGDP, lagged one year for ENSO, and distributed at lags 1 and 2 for volcanic activity.

SBC, AIC, and AICC cannot be used to compare goodness of fit between models with different values of the outcome variable (due to different methods of detrending) but they are appropriate to compare the goodness of fit between models in which the same set of observations of an outcome variable is explained with different sets of covariates. For instance, we can compare different models in which variables have been HP-detrended with $\gamma = 100$ (that is, models A1, B1, C1, and D1 in Table 2). Among these four models, model A1 including the three variables is the one that minimizes SBC, AIC, and AICC. Dropping either WGDP, ENSO activity, or volcanism reduces the explanatory value of the model. The same is also applicable to the models in which detrending has been done by subtracting a moving average. Models A3 and A4 seem to be preferable to other models with the same detrending and outcome variable data. The same cannot be said of models in which detrending has been done through the use of the HP filter with $\gamma = 6.25$. In this type of model, SBC is minimized in model C2, which does not include WGDP, but model A2, which does include WGDP, minimizes AIC and AICC. We believe this discrepancy is due to the fact that the WGDP effect is strongest at moderately high frequencies, which are largely removed by the HP filter when $\gamma = 6.25$ is used. For the same reason the correlation of WGDP and CO_2 concentrations is the weakest, 0.28, though still significant ($P < 0.05$) when the two series are detrended with the HP filter using $\gamma = 6.25$ (Table 1, panel B).

The parameter estimates for the effect of WGDP on CO_2 concentrations (for instance, 0.25 in model A1, 0.78 in model B4, Table 2) indicate that for each trillion that WGDP deviates from trend, CO_2 atmospheric levels deviate from trend, in the same direction, between a fourth and three-fourths—about a half—of a part per million.

In summary, regression analysis with the available data for the years 1960–2010 indicates that the three variables WGDP, ENSO, and volcanic activity are significant in determining the annual growth of CO_2 atmospheric concentrations. Eliminating any of them reduces the ability of the statistical models to explain the evolution of atmospheric levels of CO_2 in that time period.

4. Discussion

The evolution of CO_2 concentrations, ENSO activity, and WGDP in the years 1960–2010 (Fig. 3) suggests that the annual growth of CO_2 concentrations was in phase with both the annual growth of WGDP and ENSO activity before 1990 and in recent years. When the ENSO index is plotted lagged one year (Fig. 4, as suggested by crosscorrelations and regression results) the 1996–2010 period is consistent with ENSO forcing. In 1982–1996, WGDP and lagged ENSO happened to be out of phase and WGDP often seemed to have the dominant effect. This and the coincidences of the oscillations of the rate of growth of the world economy with volcanism and ENSO activity (Fig. 3) may have blurred the relation between these

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[3] Though we report only correlations at lag -1, 0, or 1 (Table 1), we examined cross-correlations with lags up to 7. For the correlation between population and atmospheric CO_2 we could not find any significant correlation at any lag.

Table 2 – Estimates (β), with their standard errors (SE), of the effect of world GDP, *El Niño* Southern oscillation (ENSO) activity, and volcanism on CO_2 atmospheric concentrations in models in which the dependent variable and the explanatory variables have all been similarly detrended, by subtracting a Hodrick–Prescott (HP) trend with smoothing parameter set either to 100 or 6.25, or a centered moving mean (cMM) with a window of either 7 or 9 years.

Model and de trending method		World GDP		ENSO activity				Volcanic activity						Fit statistics				
		Lag 0		Lag 0		Lag 1		Lag 0		Lag 1		Lag 2						
		β	SE	β	SE	β	SE	β	SE	β	SE	β	SE	SBC	AIC	AICC	R^2	d
A1	HP100	0.25	0.12^{*}	−0.01	0.07	0.29	0.07^{***}	−0.02	0.08	−0.24	0.09^{*}	−0.20	0.08^{*}	33.8	20.4	23.1	0.58	1.32
A2	HP6.25	0.19	0.12	0.04	0.05	0.31	0.05^{***}	−0.04	0.07	−0.25	0.07^{***}	−0.14	$0.07^{\dagger}$	0.8	−12.6	−9.9	0.57	2.02
A3	cMM7	0.45	0.19^{*}	0.00	0.06	0.32	0.06^{***}	−0.01	0.10	−0.24	0.09^{**}	−0.11	0.09	23.1	10.7	13.9	0.59	1.75
A4	cMM9	0.41	$0.21^{\dagger}$	−0.01	0.07	0.31	0.07^{***}	0.01	0.10	−0.23	0.10^{*}	−0.18	$0.09^{\dagger}$	31.2	19.2	22.6	0.61	1.50
B1	HP100	0.43	0.15^{**}	−0.04	0.08	0.17	0.08^{*}	–	–	–	–	–	–	51.8	44.0	44.9	0.24	1.11
B2	HP6.25	0.29	0.14^{*}	0.01	0.06	0.23	0.06^{***}	–	–	–	–	–	–	14.2	6.4	7.3	0.29	1.66
B3	cMM7	0.66	0.21^{**}	−0.01	0.07	0.23	0.07^{**}	–	–	–	–	–	–	31.8	24.7	25.8	0.35	1.51
B4	cMM9	0.78	0.23^{**}	−0.01	0.08	0.20	0.08^{*}	–	–	–	–	–	–	43.5	36.6	37.8	0.31	1.20
C1	HP100	–	–	−0.02	0.07	0.31	0.07^{***}	−0.06	0.08	−0.25	0.10^{*}	−0.23	0.08^{**}	34.4	23.0	24.9	0.54	1.25
C2	HP6.25	–	–	0.02	0.05	0.32	0.05^{***}	−0.06	0.07	−0.26	0.07^{***}	−0.15	0.07^{*}	−0.1	−11.5	−9.6	0.55	1.96
C3	cMM7	–	–	−0.02	0.06	0.32	0.06^{***}	−0.07	0.09	−0.24	0.09^{**}	−0.16	$0.09^{\dagger}$	24.6	13.9	16.2	0.53	1.70
C4	cMM9	–	–	−0.03	0.07	0.31	0.07^{***}	−0.05	0.10	−0.23	0.10^{*}	−0.23	0.09^{*}	31.6	21.2	23.6	0.57	1.48
D1	HP100	0.30	0.14^{*}	–	–	–	–	−0.06	0.10	−0.13	0.11	−0.19	$0.10^{\dagger}$	44.9	35.4	36.7	0.39	1.55
D2	HP6.25	0.23	0.15	–	–	–	–	−0.07	0.10	−0.13	0.09	−0.14	0.09	23.1	13.5	14.9	0.22	2.09
D3	cMM7	0.47	$0.25^{\dagger}$	–	–	–	–	−0.04	0.13	−0.12	0.11	−0.11	0.11	41.1	32.3	33.9	0.26	1.85
D4	cMM9	0.42	0.25	–	–	–	–	−0.06	0.12	−0.10	0.12	−0.20	$0.11^{\dagger}$	42.1	33.6	35.3	0.39	1.65

Note: Sample size is 49 when variables are HP-detrended, 41 when the cMM7 filter is used, and 39 when the cMM9 is used; d is the Durbin–Watson statistic.

[*] $P < 0.05$.

[**] $P < 0.01$.

[***] $P < 0.001$.

[†] $P < 0.1$.

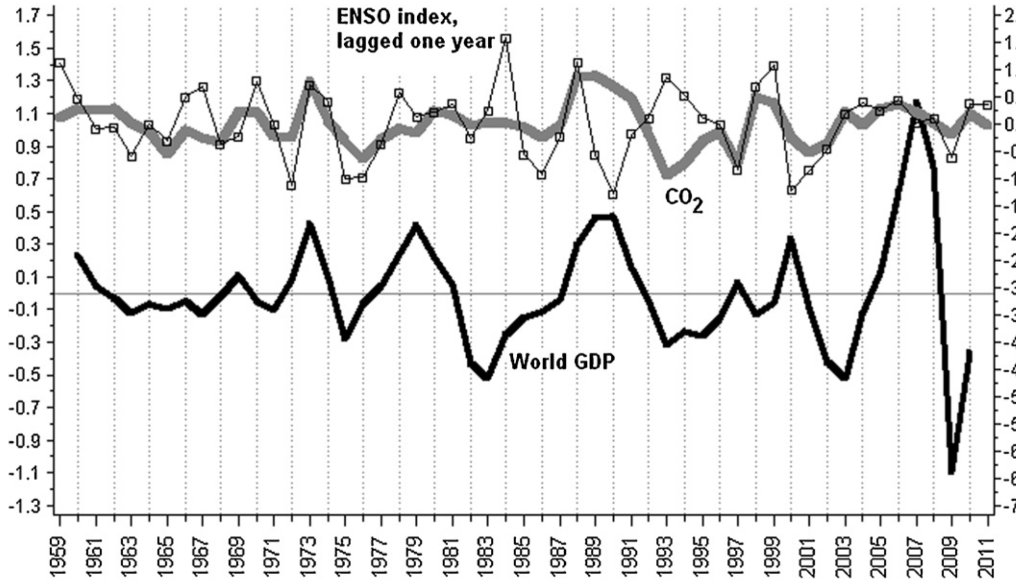

Fig. 4 – ENSO index, lagged one year (right scale), CO_2 atmospheric concentrations (ppm, right scale), and world GDP (trillion 2000 US$, left scale), all detrended with the Hodrick–Prescott filter, $\gamma = 100$.

three variables and the growth of CO_2 levels. For that reason it is essential to consider the results of the multivariate analysis (Table 2) which to a reasonable degree allow us to disentangle the relation between the variables.

Natural scientists generally agree on the effect of volcanic activity in cooling the atmosphere and retarding global warming, but differing mechanisms have been proposed to explain the cooling effect of volcanic eruptions. One proposed mechanism is related to the veil of debris thrown into the atmosphere by the eruption, which would reduce the amount of absorbed solar radiation during several months (Trenberth and Dai, 2007). Another proposed mechanism is aerosols due to volcanic eruptions reducing the incoming solar radiation. Sulfur dioxide (SO_2) emitted into the atmosphere by active volcanoes and in turn raising sulfate aerosol particles in the atmosphere would be in this view the mechanism for the cooling, which it has been suggested could be used for geoengineering (Wigley, 2006). For other authors, however, SO_2 would be a contributor to atmospheric warming. Emissions of SO_2 would raise the levels of stratospheric water vapor, which increased in 1980–2000, probably as a result of rising SO_2 emissions from Asia (Notholt et al., 2005), and likely contributed to atmospheric warming (Solomon et al., 2010). From this perspective, rising levels of stratospheric water vapor due to increasing SO_2 could contribute to atmospheric warming so that SO_2 would be a possible major contributor to climate change (Solomon et al., 2010; Shindell, 2001; Ward, 2009).

The former has to do with direct temperature effects of SO_2 or volcanism, while what our regression results show is a direct effect of volcanic activity in reducing the growth of atmospheric CO_2. As we mentioned before, the usual mechanism invoked for volcanism reducing the rate of increase of atmospheric CO_2 is the diffuse sunlight due to volcanic ash, which would increase tree growth and, in this way, would raise the capture of CO_2. Though this mechanism has often been cited, its existence would be in contradiction to the findings of Krakauer and Randerson (2003) who, using a global database of dated tree ring widths, found that tree growth in Northern forests since the year 1000 CE to the present had actually *decreased* during years following Pinatubo-scale volcanism. Therefore, there are major uncertainties about why after volcanic eruptions (a) global temperatures tend to cool, and (b) the atmospheric accumulation of CO_2 tends to slow down.

In recent decades, the major periods of volcanic activity were related to three eruptions, those of the Indonesian volcano Agung in 1963, the Mexican volcano El Chichón in 1982, and the Pinatubo eruption in the Philippines in 1991 (Fig. 3). High ENSO activity in 1965–1966, 1969, 1982–1983, 1981–1984 coincided with years of increased volcanism (Fig. 3), which complicates the task of sorting out the signals from volcanic eruptions and from ENSO (Trenberth and Dai, 2007). What has not been pointed out, however, is another coincidence, that of periods of slowdown in the world economy (particularly in 1975, 1982, and 1991–1993) with periods of high volcanism (Fig. 3). The cross-correlations of volcanic activity and WGDP are very positive and significant, and volcanism also reveals significant cross-correlations with ENSO activity. This, which at least with respect to volcanism and WGDP is a kind of chance colinearity (only by a fluke would recessions of the world economy and volcanic eruptions coincide in time), poses serious issues related to the relative role of volcanism and WGDP in the short-term evolution of atmospheric CO_2. We believe thorough consideration must be given to the hypothesis that the effect of volcanic activity on the growth of CO_2 levels is confounded by the simultaneity of major volcanic eruptions and important downturns of the world economy (in the mid-1970s, early 1980s, and early 1990s, Fig. 3). Another potential confounder would be the influence of volcanic activity (perhaps through emissions of SO_2 and ash) on ENSO events (Emile-Geay et al., 2008).

A review of the scientific literature reveals disparate theories about the potential mechanisms explaining effects

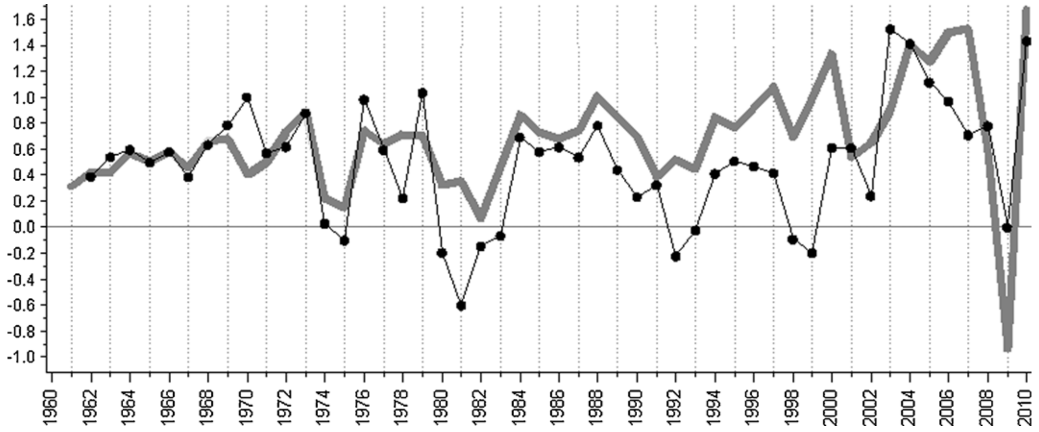

Fig. 5 – Annual growth of world GDP (gray line, trillions of 2000 US dollars), and annual change of estimated CO_2 emissions (millions of Kt, black dots).
Source: **See Appendix A.**

of volcanism on observable changes in CO_2 atmospheric concentrations. From another perspective, a link between (a) the volume of global economic activity, measured roughly by national GDPs that add up to WGDP, (b) worldwide emissions of CO_2, and, consequently, (c) CO_2 atmospheric levels would be based on the known fact that most activities generating value added to WGDP also imply combustions (Ang, 2007; Chandr Jaunky, 2011). It is true that in many countries a sizable fraction of GDP corresponds to service industries that by themselves generate less emission of CO_2 than manufacturing. However, these service activities often involve the consumption of imported goods, which implies emissions in manufacturing in the exporting countries, and transportation, a major source of CO_2. While the increasing share of the service sector in GDP, the relocation of manufacturing to other countries, and the efficiency of reduced use of energy for concrete industrial or domestic activities may weaken the link between rising GDP and increasing CO_2 emissions at the national level, increasing worldwide manufacturing, transport of raw materials, merchandise and people, and domestic use of energy will strengthen the link between global emissions and WGDP.[4] Indeed, two thirds of the increase in the growth of CO_2 concentrations in 2000–2007 has been attributed to increasing global economic activity (Canadell et al., 2007), and the physicochemical intensity of WGDP (measured either in estimated energy consumption per dollar, or in CO_2 estimated emissions per dollar) increased in 2000–2005, reversing a decline before 2000 (Pielke et al., 2008). Last and probably most important, for the global economy the evolution of CO_2 estimated emissions in the past half century follows very closely the oscillations of WGDP (Fig. 5). For all these reasons we believe the use of WGDP to model the relation between atmospheric levels of CO_2 and the global economy has the advantage of obviating the complication of studying processes that at the national level may mask the overall causal link from economic activities to estimated CO_2 emissions and from these to CO_2 atmospheric concentrations.

Making causal interpretations about observed associations always requires care (Cornfield et al., 2009). We consider that the association between volcanic activity and economic activity is likely spurious, since we know of no potential mechanism to explain it. This association is nevertheless of scientific interest, since relationships (spurious or otherwise) between potential explanatory variables have consequences for interpreting their relationship with the response variable. By contrast, investigating the evidence for or against a potential causal relation between fluctuations in atmospheric CO_2 growth and WGDP was a primary objective of our analysis. Potential mechanisms are clear, and so there is little reason to suppose that this observed association is spurious.

5. Conclusion

The major conclusion of our study is that the annual growth of atmospheric CO_2 levels is strongly dependent on the absolute growth of the world economy, so that the annual absolute increase of WGDP is a key variable to capture the annual increase in atmospheric CO_2. We have also shown that in the short run, CO_2 concentrations are not linked to demographic growth. Finally, we found that the statistical evidence for the role of volcanic activity and ENSO as short-term determinants of atmospheric CO_2 is strong for ENSO, but not for volcanic activity. Indeed, the supposed effect of volcanic activity on CO_2 atmospheric levels based on volcanic events during the past half century may well be the consequence of a statistical fluke.

Our study provides substantive evidence that in the short run, world economic activity is a major determinant of rising CO_2 concentrations (we also show that estimated CO_2 emissions closely follow the oscillations of the world econo-

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[4] Although energy efficiency has improved in recent decades, CO_2 emissions have not been declining, but steadily increasing. This has been explained by the so-called "rebound effect" or Jevons paradox. Technological progress that increases the efficiency with which a resource is used tends to reduce the unit price of the resource and increase (rather than decrease) the quantity consumed. In this way, increasing efficiency in the use of something would tend to increase the overall physical consumption of it (and activities related), and therefore also the energy (emissions) and materials used to produce it (Blake, 2005; Polimeni et al., 2008).

my). For each trillion that WGDP deviates from trend, CO_2 atmospheric levels deviate from trend, in the same direction, about half a part per million. These findings are important because they reduce the uncertainty in the links of the causal chain implied in climate changing, and allow for quantitative estimates of the required levels of "human activity" that would reduce CO_2 concentrations if business-as-usual conditions are maintained.

Appendix A. Data sources

All data used in the analysis (Appendix A) are taken from open access sources. Mean annual concentrations of atmospheric CO_2 (in parts per million by volume) are taken from CO_2Now.org, where they are referenced as data provided by the U.S. National Oceanic and Atmospheric Administration, NOAA. World GDP (in trillions of 2000 constant U.S. dollars) is from the World Development Indicators database (data.worldbank.org/data-catalog/world-development-indicators) of the World Bank. The same source provided figures of world population (millions, taken from the United Nations Population Division) and estimated emissions of CO_2 (million Kt) for the years 1961-2008. Data on CO_2 emissions for 2009 and 2010 were computed from preliminary estimates of carbon emissions obtained from CDIAC (cdiac.ornl.gov/trends/emis/perlim_2009_2010_estimates.html) in March 2012. To transform carbon emissions into CO_2 emissions the factor 3.67 was used. Bimonthly figures for ENSO activity were taken from NOAA sources (www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/table.html), where the data posted are attributed to Klaus Wolter (U.S. Department of Commerce, NOAA, Earth System Research Laboratory, Physical Sciences Division). The annual index of ENSO activity (AIEA) was computed as follows:

AIEA = [DECJAN + JANFEB + FEBMAR + MARAPR + APRMAY + MAYJUN + JUNJUL + JULAUG + AUGSEP + SEPOCT + lag(OCTNOV) + lag(NOVDEC)]/12, where DECJAN is the value for December–January, JANFEB is the value for January–February, etc., and lag(OCTNOV) is the value for October–November of the former year. The index of volcanic activity is from NOAA (ftp.ncdc.noaa.gov/pub/data/paleo/climate_forcing/volcanic_aerosols/ammann2003b_volcanics.txt), where Ammann et al. (2003) is cited as the original source. This index is computed from monthly estimated sulfate aerosols for 64 bands of 2.8° of latitude and for the years 1890–1999. The annual volcanic activity is a weighted mean of the 64 bands, with the areas of the bands used as weights. Volcanic activity for the years 2000–2010 was set equal to zero following Raupach et al. (2008). In spite of appearances, the 2010 eruption of the Icelandic volcano Eyjafjallajokull was considered by volcanologists far from the scale of the Pinatubo eruption, which emitted about 100 times as much ash as Eyjafjallajokull; the aerosols emitted by Eyjafjallajokull were also considered unlikely to have a strong effect on the climate system (Black, 2010).

We repeated many of the statistical analyses presented in the paper using shorter WGDP series from Maddison (2003) (to 2001 only), from the International Monetary Fund (1980–2007) and from the Department of Economic and Social Affairs of the United Nations (1970–2007), as well as annual estimates of the world population from Maddison (2003), and from the U.S. Census Bureau. Using these alternative series, we obtained estimates of the change and evolution of the annual volume of the world economy and world population quite similar to those we presented. The correlation and regression results with these alternative series were in line with those presented, though generally indicating a stronger short-term link between WGDP and CO_2 concentrations.

Data used in the analysis. See Appendix A for units and sources.

Year	CO_2 atmospheric concentrations	World GDP	World population	ENSO activity	Volcanic index	CO_2 emissions
1958				0.9054	0.0042	
1959	315.97			0.2698	0.0027	
1960	316.91	7.23	3027	−0.2568	0.0024	
1961	317.64	7.54	3069	−0.2322	0.0024	9.5
1962	318.45	7.97	3123	−0.7650	0.0024	9.8
1963	318.99	8.38	3189	−0.1629	1.8454	10.4
1964	319.62	8.95	3255	−0.4784	2.1758	11.0
1965	320.04	9.45	3323	0.3252	0.9864	11.5
1966	321.38	10.03	3393	0.5084	0.3699	12.1
1967	322.16	10.49	3464	−0.5792	0.1407	12.4
1968	323.04	11.15	3535	−0.4543	0.4533	13.1
1969	324.62	11.82	3610	0.5253	0.9221	13.9
1970	325.68	12.22	3685	−0.2906	0.4194	14.9
1971	326.32	12.72	3763	−1.4293	0.1606	15.4
1972	327.45	13.46	3838	0.3973	0.0750	16.0
1973	329.68	14.34	3913	0.0973	0.0277	16.9
1974	330.18	14.56	3989	−1.2804	0.0506	17.0
1975	331.08	14.71	4063	−1.1957	0.6838	16.9
1976	332.05	15.46	4135	−0.4975	0.3900	17.8
1977	333.78	16.10	4208	0.5550	0.1559	18.4
1978	335.41	16.81	4282	0.2286	0.0661	18.7
1979	336.78	17.51	4358	0.4198	0.0259	19.7

(Continued)

Year	CO$_2$ atmospheric concentrations	World GDP	World population	ENSO activity	Volcanic index	CO$_2$ emissions
1980	338.68	17.84	4434	0.6622	0.0095	19.5
1981	340.10	18.19	4512	0.1056	0.0036	18.9
1982	341.44	18.26	4592	0.6713	1.8349	18.7
1983	343.03	18.72	4673	2.0261	2.1286	18.7
1984	344.58	19.58	4753	−0.1022	0.9159	19.4
1985	346.04	20.31	4835	−0.4503	0.3478	20.0
1986	347.39	20.99	4920	0.2498	0.1288	20.6
1987	349.16	21.72	5008	1.6098	0.0474	21.1
1988	351.56	22.73	5096	−0.0918	0.0174	21.9
1989	353.07	23.59	5184	−0.7934	0.0064	22.3
1990	354.35	24.28	5272	0.3286	0.0028	22.6
1991	355.57	24.67	5358	0.6473	1.6570	22.9
1992	356.38	25.18	5439	1.4125	3.6511	22.7
1993	357.07	25.63	5520	1.0715	1.6602	22.6
1994	358.82	26.48	5601	0.6323	0.6372	23.0
1995	360.80	27.24	5683	0.4887	0.2508	23.5
1996	362.59	28.16	5762	−0.3978	0.0923	24.0
1997	363.71	29.24	5843	1.0968	0.0339	24.4
1998	366.65	29.93	5922	1.4242	0.0125	24.3
1999	368.33	30.92	6001	−0.9268	0.0046	24.1
2000	369.52	32.25	6080	−0.6163	0.0000	24.8
2001	371.13	32.79	6157	−0.2561	0.0000	25.4
2002	373.22	33.44	6233	0.3815	0.0000	25.6
2003	375.77	34.33	6308	0.5588	0.0000	27.1
2004	377.49	35.74	6383	0.3588	0.0000	28.5
2005	379.80	37.01	6458	0.5155	0.0000	29.7
2006	381.90	38.50	6534	0.0297	0.0000	30.6
2007	383.77	40.04	6610	0.0373	0.0000	31.3
2008	385.59	40.61	6687	−0.7808	0.0000	32.1
2009	387.38	39.68	6764	0.1103	0.0000	32.1
2010	389.78	41.35	6841	0.0022	0.0000	33.5
2011	391.57			−1.0368		

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